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# A TECHNICAL EVALUATION OF SEVERAL PERSONAL α-DOSIMETERS IN CANADIAN URANIUM MINES

J. BIGU, R.J. TREMBLAY, D.W. CARSON AND M.G. TOWNSEND

ELLIOT LAKE LABORATORY

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# A TECHNICAL EVALUATION OF SEVERAL PERSONAL α-DOSIMETERS IN CANADIAN URANIUM MINES

by

J. Bigu*, R.J. Tremblay**, D.W. Carson** and M.G. Townsend***

## ABSTRACT

Four personal α-dosimeter prototypes were evaluated at several locations underground at two Elliot Lake uranium mines for a total period of time of six months. The evaluation was divided into several underground tests of up to 4 weeks in duration. Three kinds of dosimeters were evaluated: two dosimeter prototypes were of the thermoluminescent (TLD) type, one prototype used a plastic material as an α-particle detector, i.e., track-etch dosimeter, and one prototype was of the electronic type and used a diffused-junction solid-state detector. All dosimeters tested were of the active kind, i.e., they used a low 'flow rate sampling' pump to sample air through a filter facing an α-detector of the kind indicated above.

Other instruments were used for grab-sampling to determine independently the radiation variables, barometric pressure, air flow, air velocity, temperature and relative humidity during the dosimeter tests.

The dosimeters evaluated were:

| | | |
|---|---|---|
| Track-etch | : | 16 units |
| H & H | : | 6 units |
| TLD/CAMPED | : | 6 units |
| α-NUCLEAR | : | 6 units. |

The factors evaluated were pump flow rate constancy, pump durability, reproducibility of results, agreement with grab-sampling tests, filter loading, contamination and mechanical and electrical problems, as well as preference by the miner wearing the dosimeter.

No one dosimeter type was superior in all the factors evaluated, and the miners showed no particular preference for a specific dosimeter. The tests carried out here show that the α-NUCLEAR and track-etch dosimeters

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* Research Scientist, Elliot Lake Laboratory, MRL, ** Technologist, MSL and *** Research Scientist, MSL, Ottawa, CANMET, Energy, Mines and Resources Canada.

performed better than the other prototypes tested under the particular environmental conditions of the test. In general, the Working Level (WL) evaluated by personal dosimetry was lower than that obtained by grab-sampling techniques.

Both the track-etch and α-NUCLEAR dosimeters were of the old type. A technical evaluation of the new improved prototypes recently available should be performed, and this will be done at the Elliot Lake Laboratory (CANMET) for the α-NUCLEAR dosimeters as part of the long established test program on this subject.

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# INTRODUCTION

Personal radiation dosimeters have been developed to estimate the exposure of occupational workers to different kinds of radiation.

Several personal α-particle dosimeters have been designed to determine the exposure of miners to α-radiation in underground uranium mines. Personal α-dosimeters are time-integrating devices that are usually calibrated in terms of α-radiation exposure, e.g., Working Level Month (WLM) or Working Level Hour (WLH). A personal α-dosimeter consists essentially of a highly efficient pump, a sampling head (housing an adequate filter) and an α-detector facing the active side of the filter. Air flows through the filter where the decay products of radon (and thoron) are deposited. α-particles emitted by the α-emitters RaA and RaC' (and also ThC and ThC') are detected by an appropriate detector, e.g., a thermoluminescent detector (TLD), a track-etch detector (e.g., cellulose nitrate) or a silicon-diffused or surface-barrier detector. According to the kind of detector used, personal α-dosimeters have come to be known as TLD dosimeters (TLDD), track-etch dosimeters (TED) or solid-state (electronic) dosimeters (SSED). Some of these dosimeters are still under continuous research and development or technical evaluation in uranium mines.

The need for a reliable α-dosimeter has been recognized for some time. However, there is no single personal dosimeter that combines the broad spectrum of practical requirements including: being inexpensive to build, rugged, simple to maintain and retrieve information from, has long-time reliability, and is, in addition, responsive to the ever growing need for discriminating the thoron progeny present in relatively high amounts in some Canadian uranium mines.

The choice of one dosimeter type over another must be based on a number of factors including long-term reliability, ruggedness, initial

investment and routine maintenance, ease of operation and data processing and retrieval. In spite of the obvious benefit of personal α-dosimeters in the estimation of exposure of uranium miners their use is not widespread, there being only a few mines where α-dosimeters are employed on a routine basis.

This report presents data pertaining to an underground technical evaluation of four personal α-dosimeter prototypes carried out in two Elliot Lake (Ontario) uranium mines. The dosimeter prototypes tested include the alpha-NUCLEAR electronic dosimeter, the CEA (Commisariat à la Energie Atomique) track-etch dosimeter, the H & H Custom Works TLD dosimeter and the TLD/CAMPED dust/radiation sampler. A brief technical description of these prototypes is given below. The results of some preliminary studies on some of the above dosimeters have been published elsewhere (1,2,3,4).

The technical evaluations conducted by CANMET and the contracts awarded by CANMET to private industry are part of a long-term program and continuous effort aimed at evaluating and stimulating the development of advanced instrumentation for better environmental and personal exposure monitoring.

## DESCRIPTION OF THE DOSIMETERS

For simplicity, the Alpha-NUCLEAR dosimeter, the CEA Track-etch dosimeter and the H & H Custom Works TLD dosimeter will be referred to hereafter as the α-NUCLEAR, track-etch and H & H dosimeters, respectively.

### THE α-NUCLEAR DOSIMETER

The dosimeter is a compact, rugged and lightweight unit consisting of a sampling head, housing an α-detector, and a filter, associated electronic circuitry and a sampling pump. The detector is a Silicon Diffused-Junction type of 400 $mm^2$ sensitive area, protected from plate-out contamination by a

thin metallized mylar sheet. The constant flow (approximately 100 cc/min) pump continuously draws air through a fibreglass or 0.8 μm Millipore filter facing the α-detector. The airborne radon and thoron decay products are deposited on the filter and their disintegration is counted by the detector, and stored within the memory. The dosimeter memory has the capability of storing 1 x $10^6$ α-counts, which is approximately equivalent to 37.5 WLH of radon daughters. The dosimeter detects in real time.

The dosimeter operates in conjunction with a standard miner's cap lamp battery to which it fits snugly. The unit is worn around the belt and has no external controls, which prevents the unit from being accidentally misused. The filter is changed everyday before the shift and the data are 'read' after the shift by means of a microprocessor-controlled electronic reading network (reader), located on 'surface'.

The reader provides the controlling functions for the dosimeter. When the dosimeter is plugged into the reader the pump automatically switches off. When the dosimeter is unplugged, the pump switches on, the data on the dosimeter memory are erased, i.e., reset to zero, and a new counting period is started. After the end of sampling the dosimeter is again plugged into the reader and the accumulated data, i.e., α-counts, during the sampling period can be read. The reader is a microprocessor-controlled instrument that transfers the data from the dosimeter's memory automatically 3½ hours after the end of sampling, for radon daughters, and at two later times for thoron daughters. The reading times are programable. The data are printed automatically by a thermal printer which also displays the serial number of the dosimeter, which is electronically implanted, for the purpose of identification. A new version of the dosimeter-reader system referred to above has been described elsewhere (5).

THE TRACK-ETCH DOSIMETER

The dosimeter consists of a cylindrical Duraluminum body and a detection head. The body contains rechargeable batteries, a motor, a turbine and a switch. The twin-bearing motor drives the centrifugal turbine at 18,000 rpm. It is autonomous for about 18 hours. The detection head includes a Millipore filter and its holder, 3 collimators and associated screens (α-particle energy absorbers), and the detector film. The flow rate with the filter in place is about 100 cc/min.

Detection of α-particles is done by cellulose nitrate film (Kodak Pathé LR 115). The sensitive layer of the film is 13 μm thick and red, and is mounted on a colourless Mylar film.

The passage of α-particles in the cellulose nitrate affects the structure of the substance in such a way that if the energy of the incident particle is well chosen an appropriate chemical etching creates holes of regular dimensions in the detector with diameters of several μm. Detection of radon and thoron daughter α-emitters are effected by screens (i.e., absorbers) of different thicknesses placed on the detectors as follows. The distance covered by the α-particles in the air and the thickness of the screens are such that at the end of a collimator the α-particles emitted by the RaA and RaC' do not emerge from the screen, whereas those emitted by the ThC' emerge with a residual energy of about 3 MeV and are thus recorded. At the end of the second collimator the α-particles emitted by the RaC' emerge with a residual energy of 3 MeV and are recorded; the α-particles emitted by RaA do not emerge and those emitted by ThC', above 5 MeV, do not leave any tracks with present etching conditions. At the end of the third collimator α-particles emitted by RaC' and ThC' have energies above 5.3 MeV and do not give tracks in the detector film whereas the α-particles emitted

by the RaA emerge with an energy of 2.8 MeV and are recorded.

Tracks produced in the detector appear as luminous white patches on a red background. Tracks can be counted using an optical microscope, a spark detector, or by evaluating the density of tracks through the quantity of light transmitted by these holes. For a description of the track-etch dosimeter see (6).

THE H & H DOSIMETER

The dosimeter consists of an aluminum case and a detector head. The case contains an H & H Custom Works pump with a flow rate, with filter in place, of up to 150 cc/min, and running time of about 10 hours. The case also contains 2 NiCd rechargeable batteries. The detector head includes a Millipore filter, located on a sintered metal screen, and two thermoluminescent (TLD) chips separated by a steel plate several mm thick. One TLD chip is located about 2 mm distance facing the filter. This chip is sensitive to $\alpha$-, $\beta$- and $\gamma$-radiation, the $\alpha$-particles being totally absorbed in the chip. The second TLD chip is only sensitive to $\gamma$-radiation, as the $\beta$-particles are absorbed in the steel plate that serves as a $\beta$-shield. The different TLD readings obtained with the two TLD chips enable the dose due to $\alpha$-particles to be calculated. The TLD chips were read with a Harshaw* thermoluminescence detector Model 2000B. A brief description and preliminary testing of this dosimeter has been given elsewhere (7).

Two different TLD materials have been used: LiF and $CaF_2$:Dy, from Harshaw. Thus, some dosimeters used LiF TLD pairs, whereas the rest of the dosimeters used $CaF_2$:Dy TLD pairs. The TLD chips had the following approximate dimensions, 3.2 mm x 3.2 mm x 0.38 mm.

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* U.S.A. commercial firm.

THE TLD/CAMPED DOSIMETER

The TLD/CAMPED head is a two stage impactor which basically consists of two concentric cylindrically shaped (hollow, one side closed) parts or pieces. An approximately 3 mm orifice on each piece enables air to go through the sampler head. The two pieces are assembled so that the two orifices are exactly opposite, i.e., forming a 180° angle. Air being sampled passes through the first orifice impacting on the surface of the inner piece, where a fraction of the dust of size above 10 μm is removed. The air continues its path through the second orifice where the remaining dust particles of size above 10 μm are practically removed by a reentrant solid cylinder in the second piece. The air finally goes through a 5 mm orifice of a conically shaped piece sitting on a filter holder, housing a silver membrane filter. Dust particles in the respirable size range, approximately 1-10 μm, are deposited on the filter. The conical piece has provisions for housing two TLD detectors facing the filter below at an oblique angle. One of the TLD chips is exposed to the α-, β- and γ-radiation emitted by the radioactive products collected on the filter. This is done by placing the chip on the rim (less than 1 mm thick) of a 5 mm orifice located half-way along the side of the cone. The second chip is shielded against α-exposure by placing it as above, but allowing the rim to fully extend closing the lower part of the orifice. The two TLD chips are placed side by side, their centres being only about 5 mm apart, to ensure that they both subtend the same solid angle (approximately) relative to a given set of coordinates on the filter. This arrangement also enables "uniform" exposure. Air is sampled by a small pump with a flow rate of 2 L/min. The collection efficiency of the silver membrane filter for particles in the approximate size range 1-10 μm is practically 100%.

The outer impactor piece is machined out of stainless steel. The rest of the TLD/CAMPED head is aluminum. The vertical distance between the

centre of the chips to the filter is about 7-8 mm. The chips (LiF or $CaF_2$:Dy) have approximate dimensions 3.2 mm x 3.2 mm x 0.38 mm, and subtend an angle relative to the filter of approximately 40°. For a more detailed description of the TLD/CAMPED sampler refer to (8). Some laboratory calibration work with the sampler has been published elsewhere (4).

## EXPERIMENTAL PROCEDURE

Underground tests were conducted at Rio Algom Ltd. (Quirke II), and Denison Mines Ltd., in Elliot Lake (Ontario). Tests at each mine were divided into a short-term test of 1-2 weeks duration, for the purpose of dosimeter calibration, and several 'long-term' tests of 3-4 weeks duration, mainly for personal dosimetry.

The short-term test, hereafter referred to as site dosimetry test, consisted of placing the dosimeters in an area of the mine over which underground conditions remained reasonably constant. A variety of radiation, dust and meteorological measurements were conducted at short intervals, about 15-20 min, so that an accurate profile of the underground conditions could be obtained. The dosimeters underground sampling time and pump flow rates were accurately determined. Dosimeters were calibrated in terms of radon (and thoron) decay products by carefully comparing the dosimeters response in total integrated α-count (α-NUCLEAR), number of tracks (CEA track-etch) and light output (H & H and TLD/CAMPED) with the average mine air WLs obtained by graphical integration of the experimental data, i.e., WL(t) versus time.

In the long-term tests, hereafter referred to as the personal dosimetry tests, the majority of the dosimeters were worn by miners, except for a few dosimeters which were kept at a fixed mine location as 'controls'. Radiation and meteorological measurements were carried out at the fixed location and in

areas where miners wearing the dosimeters were working. The purpose of the 'controls' was to calibrate a reduced number (1 or 2) of each dosimeter prototype over periods of time comparable to the time the dosimeters would usually be worn on a routine basis, were a personal dosimetry program to be implemented. (For example, the suggested detector and filter change frequency, and hence dosimeter reading, is 4-weeks for the track-etch and H & H dosimeters.) For simplicity, the 'controls' study will be referred to as the long-term calibration tests.

The long-term calibration tests are important to determine the effect of filter 'loading' and contamination of the sampling head on the dosimeter radiation response. Thus, in addition to radon and thoron decay products, mineral dust, diesel exhaust particulates, lubricating oil mist and water mist in mine air are also deposited in the dosimeter's filter. As $\alpha$-particles are readily absorbed in matter even a small deposition of contaminants on the filter can produce appreciable absorption and energy degradation of $\alpha$-particles. Furthermore, because of the mechanical and air flow characteristics of the dosimeter's sampling head, long-lived radioactive dust* is deposited on the walls, detector, and other parts of the sampling head by direct impaction or attachment to surfaces, thereby contaminating the dosimeter.

The personal dosimetry tests proper were broader in scope than that of the long-term calibration study. Thus, in addition to long-term calibrations and studies on the effect of filter loading and contamination, the personal dosimetry tests were also aimed at:

1. Determining the acceptance, reaction and preference by miners to the different dosimeter prototypes tested;
2. Investigating the radiation response of the dosimeters under actual mining

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* Long-lived radioactive dust is defined here as coarse dust, i.e., above 1 μm size, containing long-lived $\gamma$- and $\alpha$-radionuclides from the U-238 and Th-232 chains, other than the usual short-lived radon and thoron progenies.

working conditions;

3. Studying the long-term mechanical (e.g., pump performance) and electronic reliability of the dosimeters;
4. Determining the long-lived radioactive dust by spectroscopic techniques.

Because of the relatively large area to cover and time and manpower limitations, the number of radiation and meteorological measurements conducted at any given location was significantly reduced as compared with the site dosimetry tests. Hence, the accuracy of the long-term and personal dosimetry calibrations was less than that corresponding to the site dosimetry. However, this limitation was more than compensated by the wealth of information obtained.

Radiation variables were determined by grab-sampling techniques. Radon daughter Working Levels, WL(Rn), were measured by the Thomas, Kusnetz and Markov methods (9,10,11). Radon daughter concentrations were determined by the Thomas method, and an α-spectroscopic technique (12), the latter in conjunction with the WL-1000B, an instrument manufactured by Pylon Industries (Ottawa), under CANMET specifications. Thoron daughter Working Levels, WL(Tn), and the concentration of ThB were determined by a technique similar to the Kusnetz method, i.e., from a total gross α-count. The WL-1000B also enabled the determination of the concentration of ThC in addition to the concentration of ThB and WL(Tn).

Meteorological variables, e.g., air flow, temperature, barometric pressure and relative humidity were measured at fixed time intervals. It was originally planned to conduct the technical evaluation of the dosimeters in conjunction with a meteorological package interfaced with a multi-head radon/radon daughter continuous monitoring system. In this fashion, radiation and meteorological variables could have been monitored at different locations simultaneously, thereby considerably increasing the amount of available data,

and with a minimum of personnel attendance. However, delays in the delivery of the instrumentation, under contract by CANMET, made continuous monitoring impossible at the time of the dosimeter tests.

Mineral dust and diesel particulate concentrations were obtained by gravimetric dust sampling techniques in conjunction with X-ray diffraction methods (13). Dust and diesel particulate size distributions were obtained by means of a Fineparticle spectrometer in conjunction with eriometric techniques (14).

The dosimeter prototypes and the number of units used in the technical evaluation were as follows:

Track-etch : 16 units

H & H : 6 units

α-NUCLEAR : 4 units

TLD/CAMPED : 6 units.

Some of the characteristics and capabilities of these dosimeters have been summarized in Tables 1 and 2.

Because of the large amount of data collected during the different underground tests, each test will be presented and discussed separately. Conclusions and recommendations derived from the analysis of all the tests will be given at the end of this report. For simplicity, the tests have been labelled according to the mine where measurements were conducted, i.e., Rio Algom and Denison Mines indicated by R.A. and D.M., respectively, followed by the test number indicated by the letter T and a number.

Table 1 - Characteristics of dosimeter prototypes tested

| Dosimeter Prototype | Detector | Pump Flow Rate | Stored Data | Processing | Reader | MFG | Filter Change |
|---|---|---|---|---|---|---|---|
| α-NUCLEAR | D-J* | ~0.1 L/min | α-counts | None | Microcomputer-based elec. reader | α-NUCLEAR (Toronto) | Daily |
| H & H | $CaF_2$:Dy, LiF | ~0.1 L/min | Light | Heating | TLD Reader | H & H (Toronto) | Monthly |
| TLD/CAMPED | $CaF_2$:Dy, LiF | 2 L/min | Light | Heating | TLD Reader | CANMET | Daily |
| Track-etch | Cellulose Nitrate | ~0.1 L/min | Tracks | Chemical Etching | Optical or spark counter | CEA (France) | Monthly |

* Diffused-junction.

Table 2 - Radiation characteristics of dosimeter prototypes tested

| Dosimeter Prototype | RnD Data[1] | TnD Data[2] | LLRD Data[3] | Frequency of Reading | Time for RnD Results[4] | Time for TnD Results[4] | Information Content[5] | Ruggedness |
|---|---|---|---|---|---|---|---|---|
| α-NUCLEAR | Yes | Yes | Not likely[+] | Daily | 2-3 min | Several hrs | High | Medium |
| H & H | Yes | No | Yes | Monthly | <½ h | N/A | Low | Medium |
| TLD/CAMPED | Yes | No | Yes | Monthly | <½ h | N/A | Low | Good |
| Track-etch | Yes | Yes | Yes | Monthly | Several hrs | Several hrs | Medium | Good |

[1]) Capability of gathering radon daughter (RnD) data.

[2]) Capability of gathering thoron daughter (TnD) data.

[3]) Capability of extracting long-lived radioactive dust (LLRD) data. TLD/CAMPED is the most suitable dosimeter for LLRD.

[4]) Time taken, after the sampling period, to process raw data (including experimental procedures) and get final results, e.g., WL.

[5]) Based on suggested use and reading frequency.

[+]) Unless very high concentration available because of frequency of filter change and low flow rate.

## UNDERGROUND TESTS AT RIO ALGOM

### R.A.T.I. - SITE DOSIMETRY RESULTS AND DISCUSSION

This test was carried out in two different sections of the mine: a conventional track mining site (no diesel machinery or tools) and a trackless, dieselized, section of the mine where mining operations were carried out with diesel machinery. The reason for having the two sections of the mine was to determine whether or not a difference in the dosimeters' behaviour under a diesel- and diesel-free atmosphere would render itself immediately obvious. The measurements were carried out over a two-week period, one week on each section of the mine. Some of the data collected during these tests have been summarized in the Figures described below.

Figure 1 gives the daily average meteorological underground conditions (barometric pressure, $P_B$, air temperature, T, relative humidity, RH, and air flow, F) for the several days of underground testing.

Figure 2 shows histograms of the frequency of occurrence for which the experimental ratios [RaB]/[RaA] and [RaC]/[RaA] have values within a given range.

Figure 3 shows the experimental values of the ratio [RaC]/[RaA] versus the experimental values of the ratio [RaB]/[RaA] on a graph showing the theoretical limiting boundaries for the above ratios as predicted by several mine models: the isolated mine model (X), the mine-tunnel model (Y), and a mine model consisting of the mixing of 'young' and 'old' air (Z). Note: the isolated mine model is defined as one in which a certain quantity of radon gas is added initially to pure air and then decays, there being no replenishment or removal of activity from the system. In the mine-tunnel model a source of radon is released at one point in the mine and then carried along with the ventilation air through the rest of the mine. Radon is constantly replenished by diffusion from the walls of the mine.

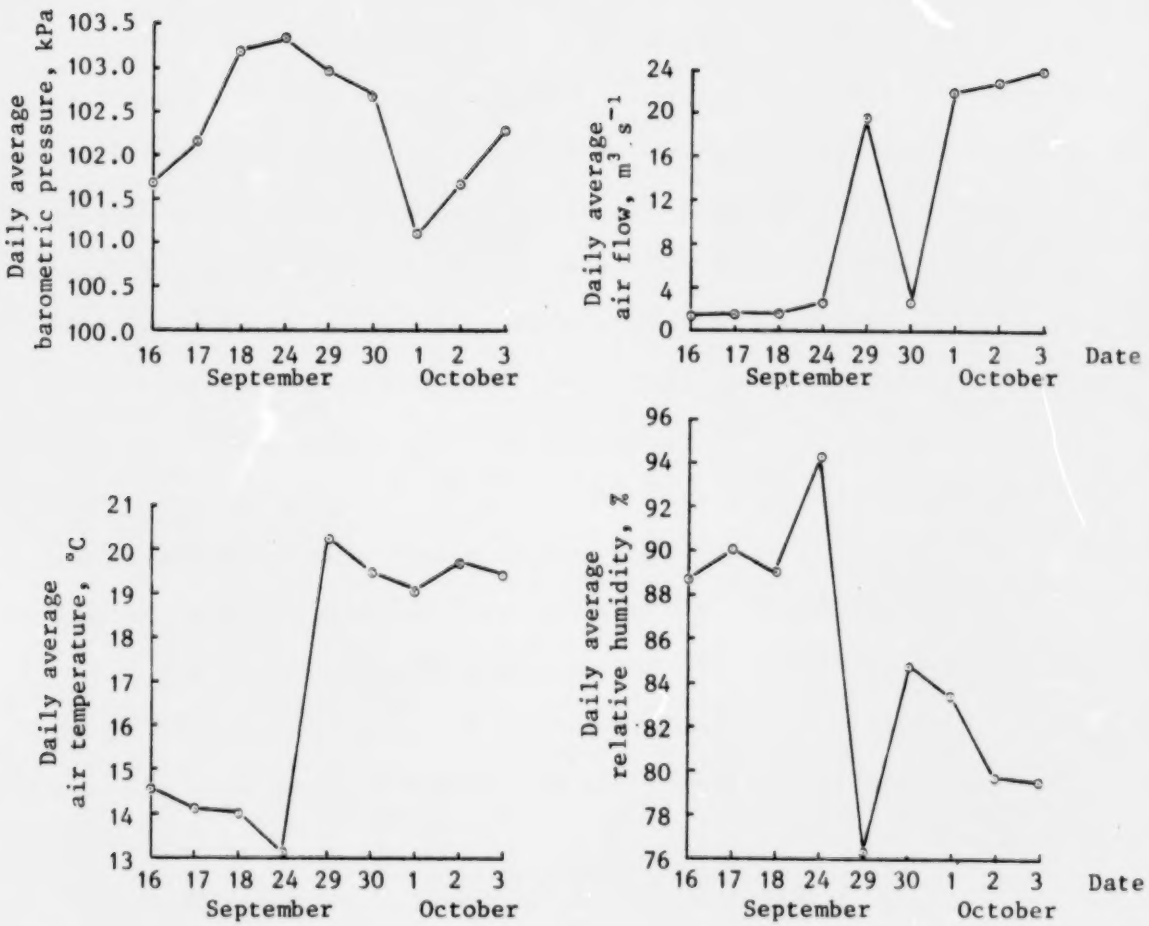



Fig. 1 - Daily average underground environmental conditions versus date.

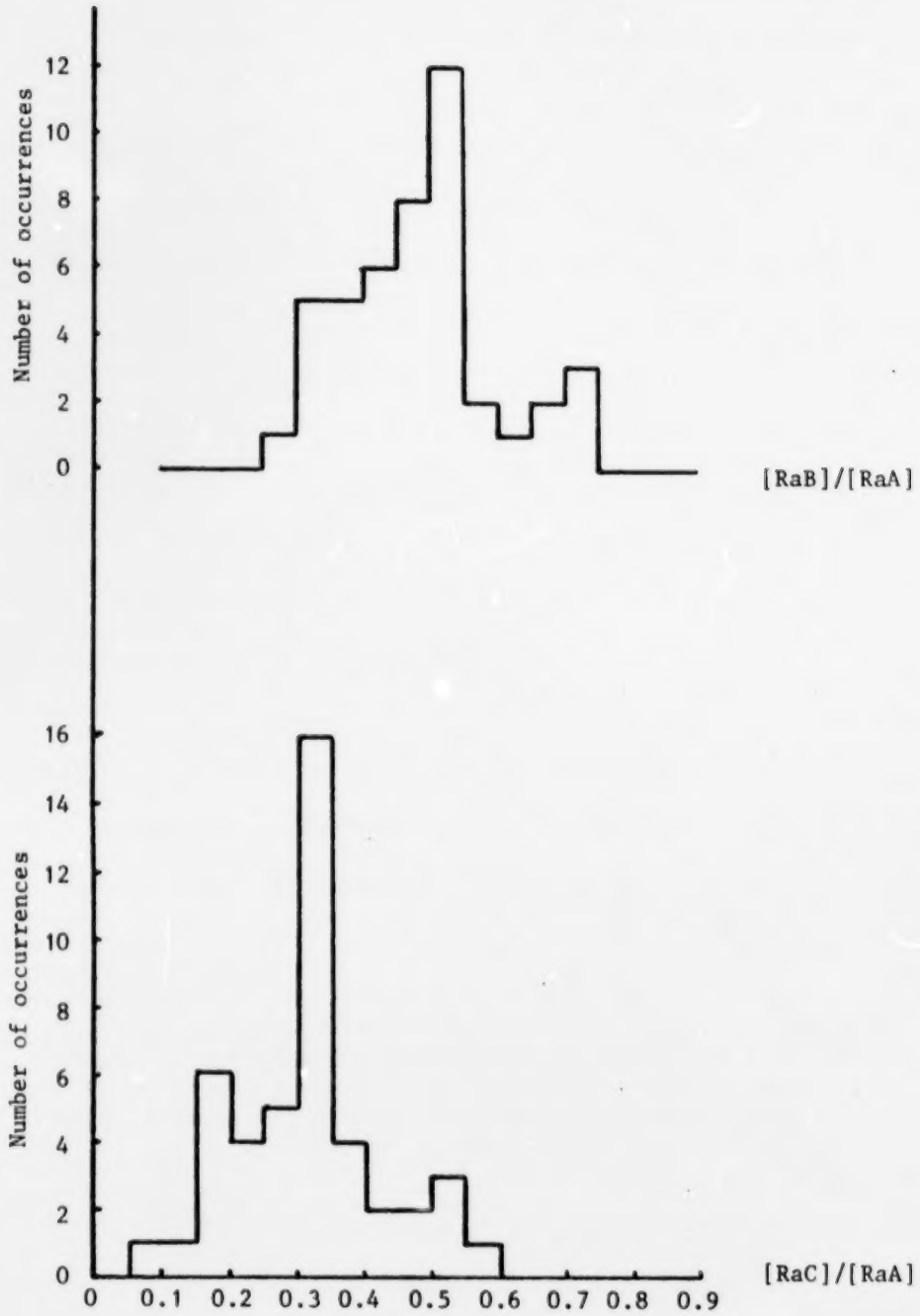



Fig. 2 - Number of occurrences versus ratios [RaB]/[RaA] and [RaC]/[RaA] from the field data.

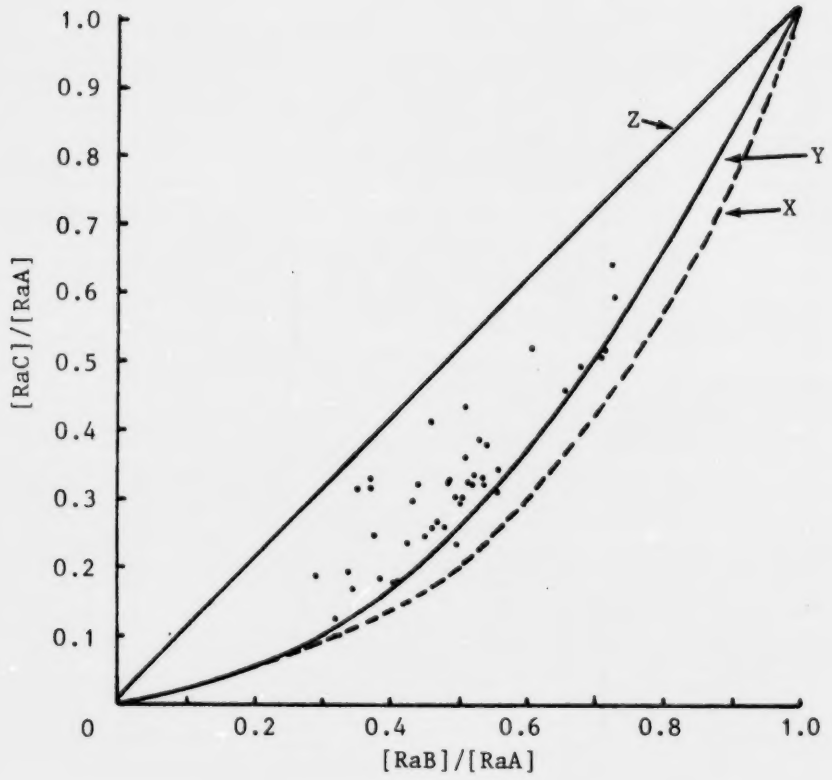



Fig. 3 - Experimental values of [RaB]/[RaA] versus [RaC]/[RaA] on a graph showing the theoretical limiting boundaries for various mine models: the isolated mine model (X), the mine-tunnel model (Y), and a mine model consisting of the mixing of 'young' and 'old' air (Z).

Figure 4 shows the experimental ratio [RaA]/WL(Rn) versus the experimental ratio [RaB]/WL(Rn) on a graph showing the theoretical limiting boundaries for these ratios according to the isolated mine model and Evans mine model (15,16).

Figure 5 shows the WL(Rn) and WL(Tn), daily averages, for the duration of the underground testing.

Figure 6 shows the WL(Tn)/WL(Rn), calculated from the daily average values of WL(Tn) and WL(Rn), for the duration of the underground testing.

Figure 7 gives the pump flow rate, Q, corresponding to two α-NUCLEAR dosimeters (DM008 and DM012) for the duration of the underground testing.

Figures 8, 9 and 10 show the pump flow rate, Q, corresponding to the H & H dosimeters for several days of underground testing.

Figures 11 to 16 give the pump flow rate, Q, corresponding to the track-etch dosimeters for several days of underground testing.

Figures 17 and 18 show the total number of α-counts, $N_\alpha$, recorded by the α-NUCLEAR dosimeters versus Working Level Hour (WLH) calculated from the daily WL(Rn) average and WL(Tn) and the dosimeters sampling time, $T_s$. The straight lines represent the best fitted lines through the data points by linear regression analysis. The upper line on each Figure represents $N_\alpha$ versus $\overline{WL}(Rn) \times T_s$. The lower line represents $N_\alpha$ versus $\overline{WL}_T \times T_s$ where $WL_T = \overline{WL}(Rn) + \overline{WL}(Tn)$. (Note: the arrow bars stand for average.)

Figure 19 gives the net TLD reading (i.e., subtraction of the shielded TLD chip reading from the unshielded TLD chip reading) versus $\overline{WL}(Rn) \times Q \times T_s$ for the H & H dosimeters. The straight lines represent best fitted lines through the data points by linear regression analysis. Upper (lower) line has been obtained using $CaF_2$:Dy (LiF) chips.

Figure 20 is similar to Fig. 19, but the TLD reading has been plotted against $\overline{WL}_T \times Q \times T_s$.

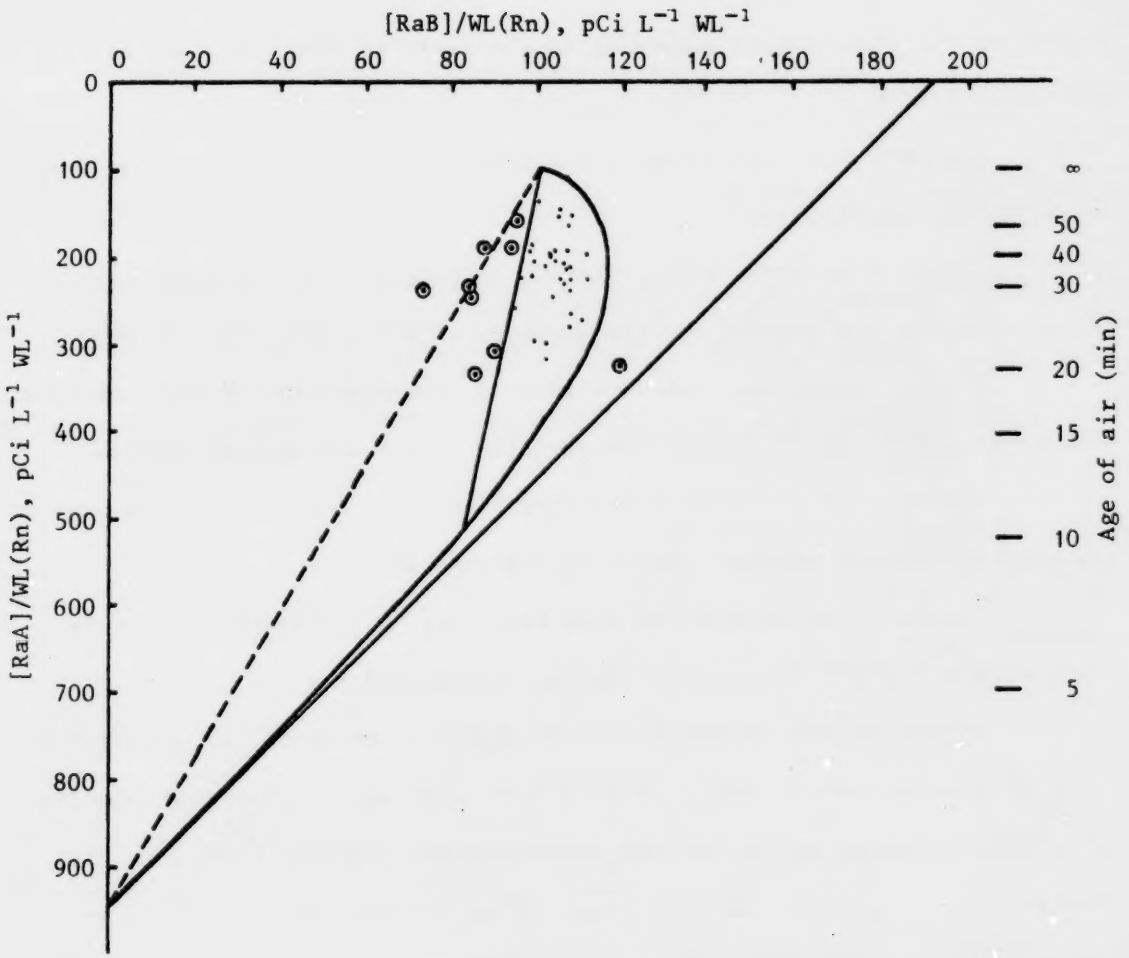



Fig. 4 - Experimental ratio [RaA]/WL(Rn) versus experimental ratio [RaB]/WL(Rn) on a theoretical graph for the isolated mine model. Data falling outside the age of air range between 10 min and ∞ min are indicated with encircled dots. Theoretical age of air is indicated by the numbers on the right hand side of the graph.

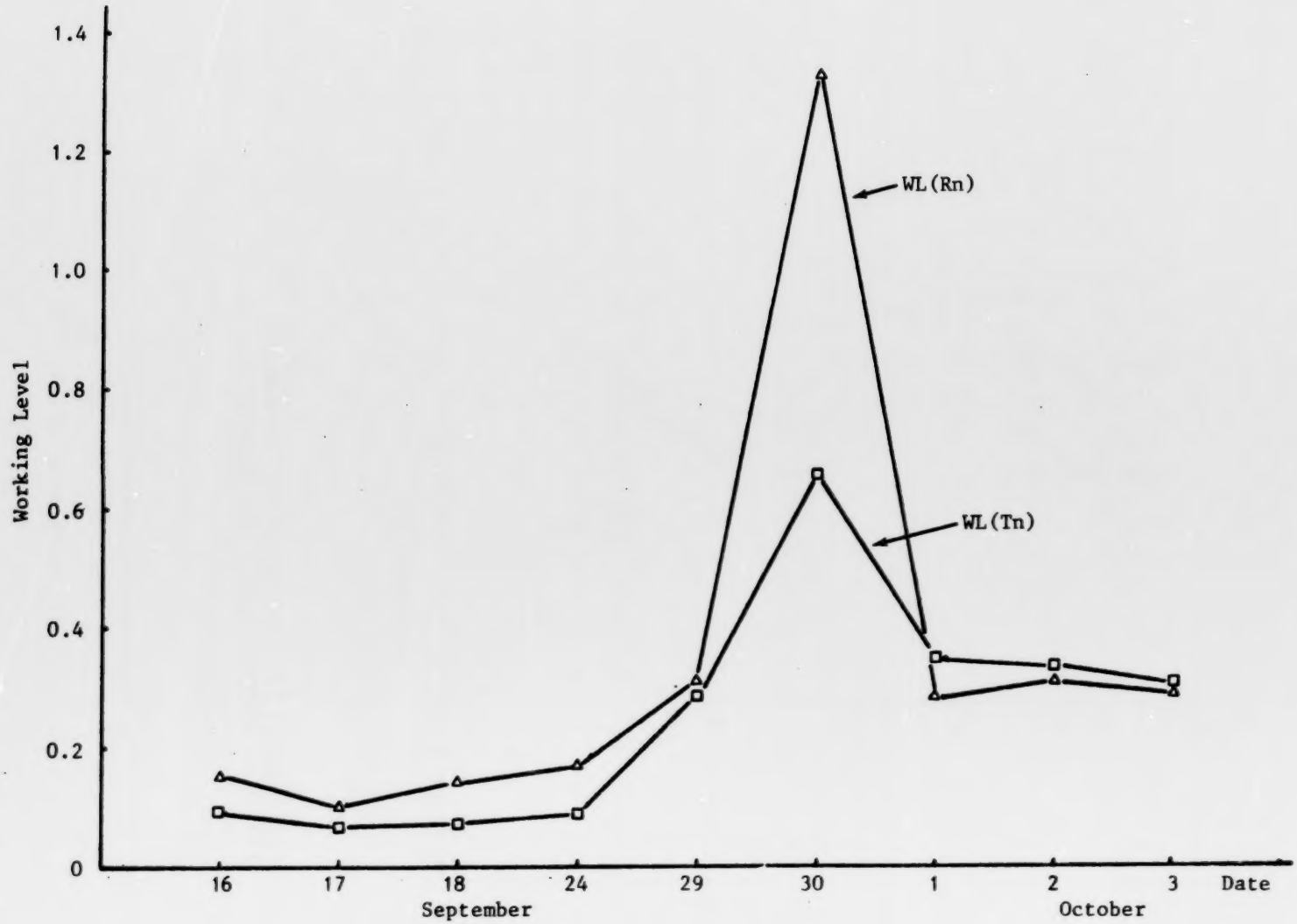



Fig. 5 - WL(Rn) and WL(Tn) versus date.

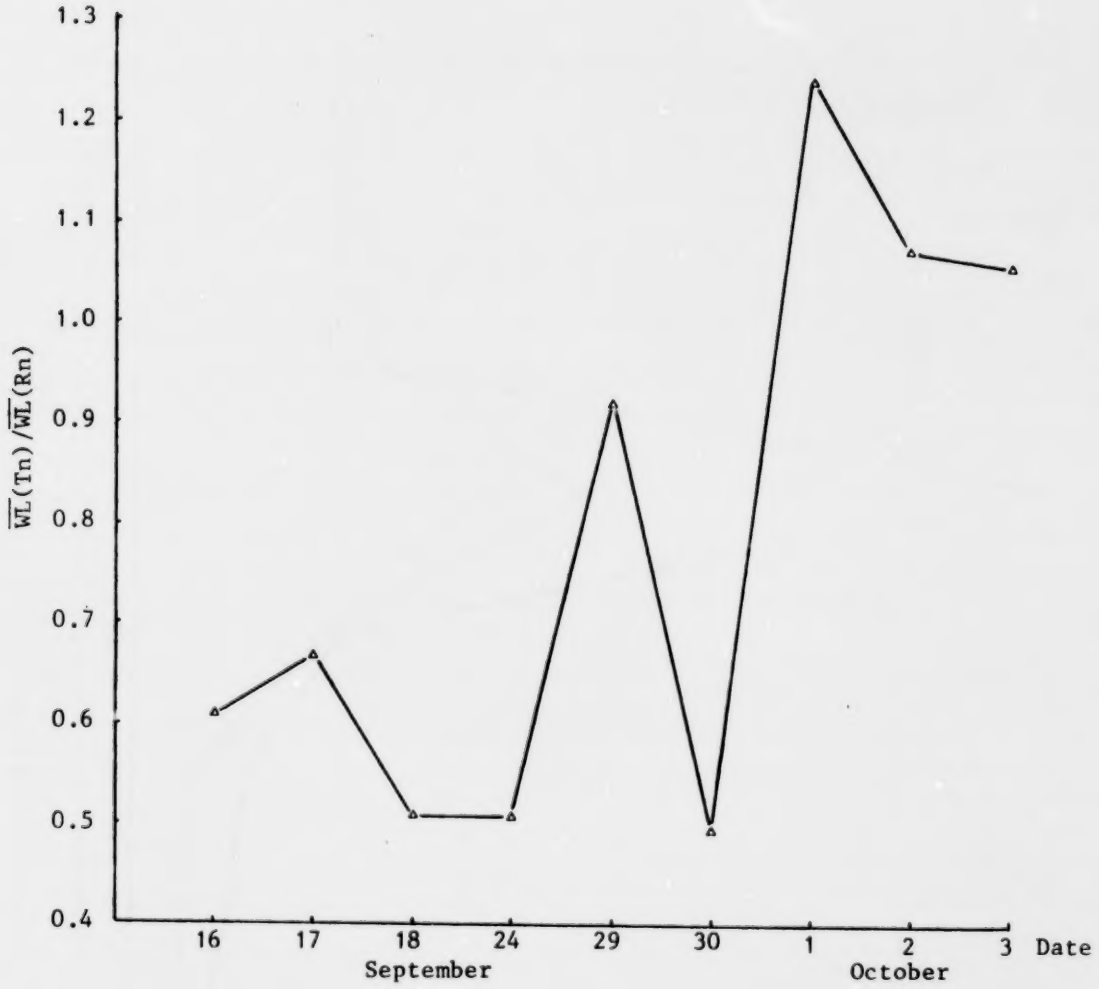



Fig. 6 - Experimental ratio WL(Tn)/WL(Rn) versus date. The bars on the symbol WL indicate the daily average.

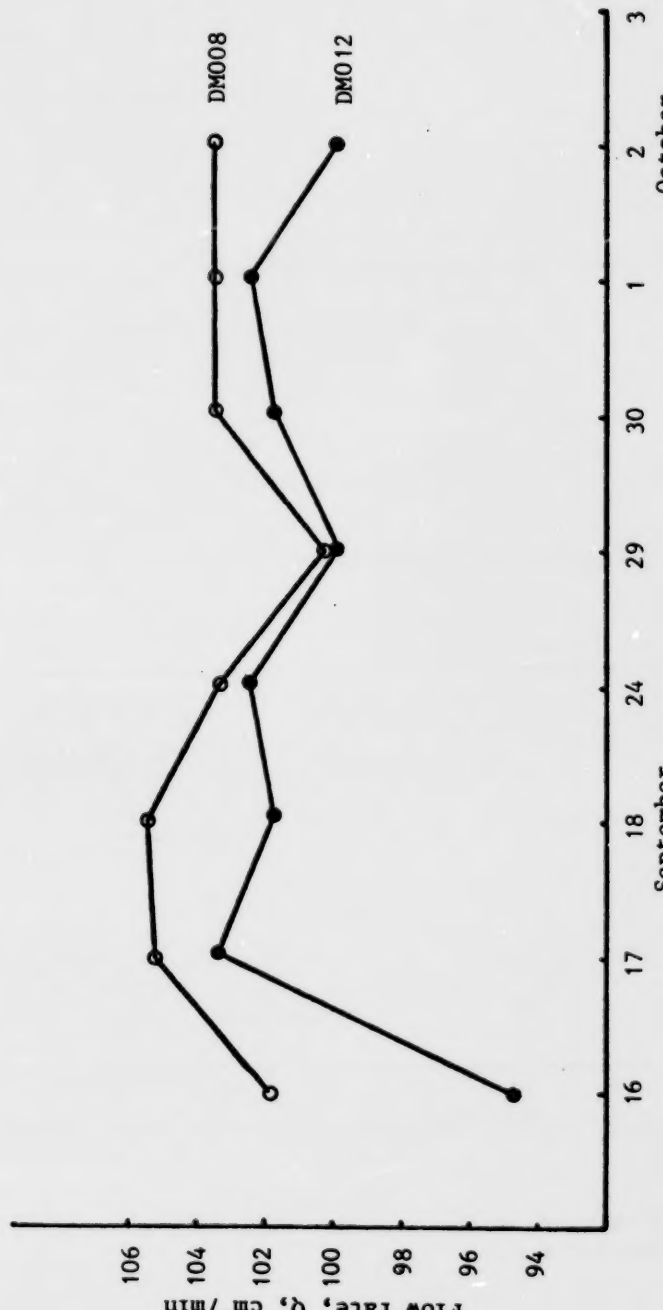



Fig. 7 - Dosimeter flow rate versus date for two $\alpha$-NUCLEAR dosimeters: DM008 and DM012.

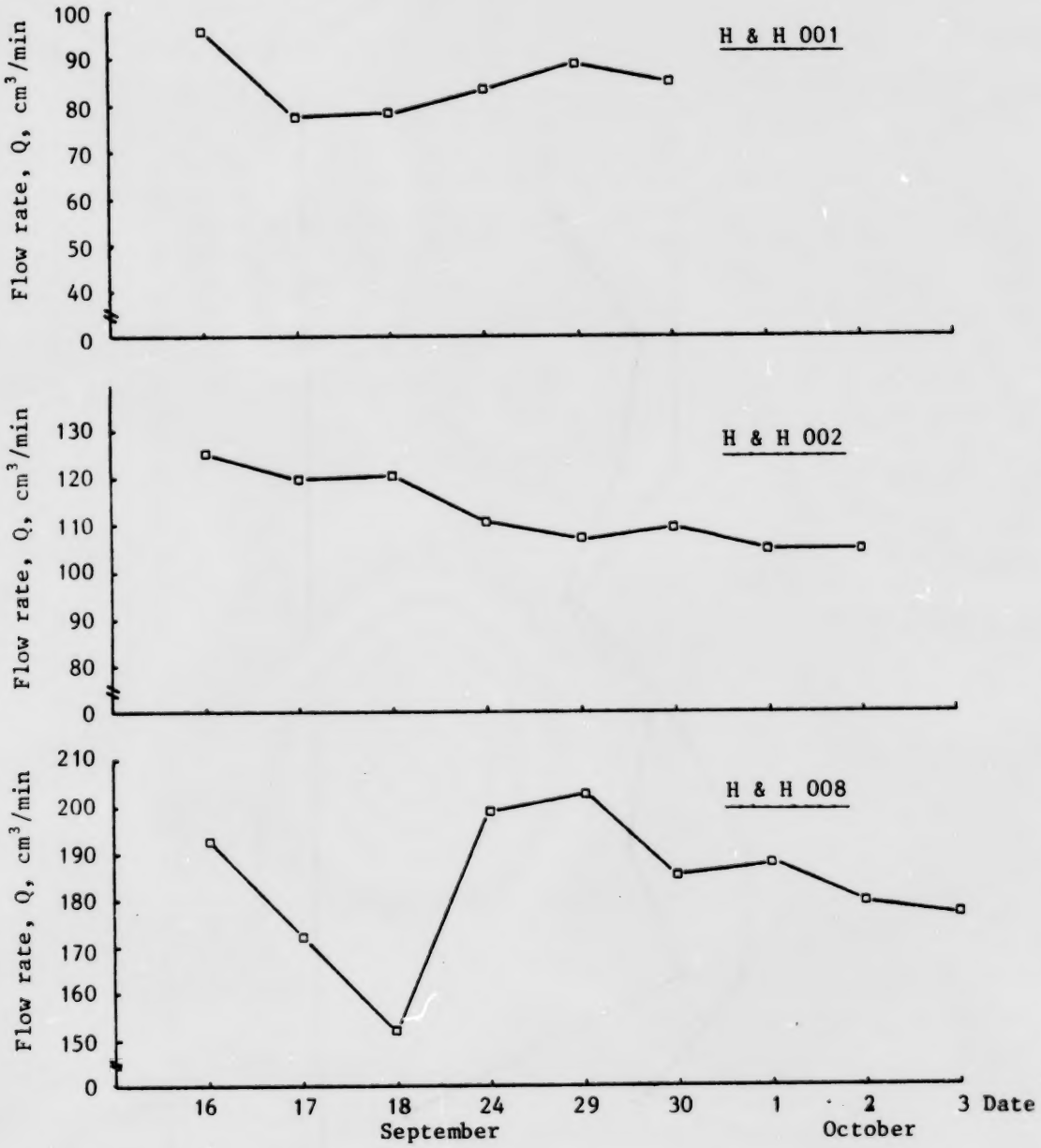



Fig. 8 - Dosimeter flow rate versus date for three H & H dosimeters: H & H 001, H & H 002 and H & H 008.

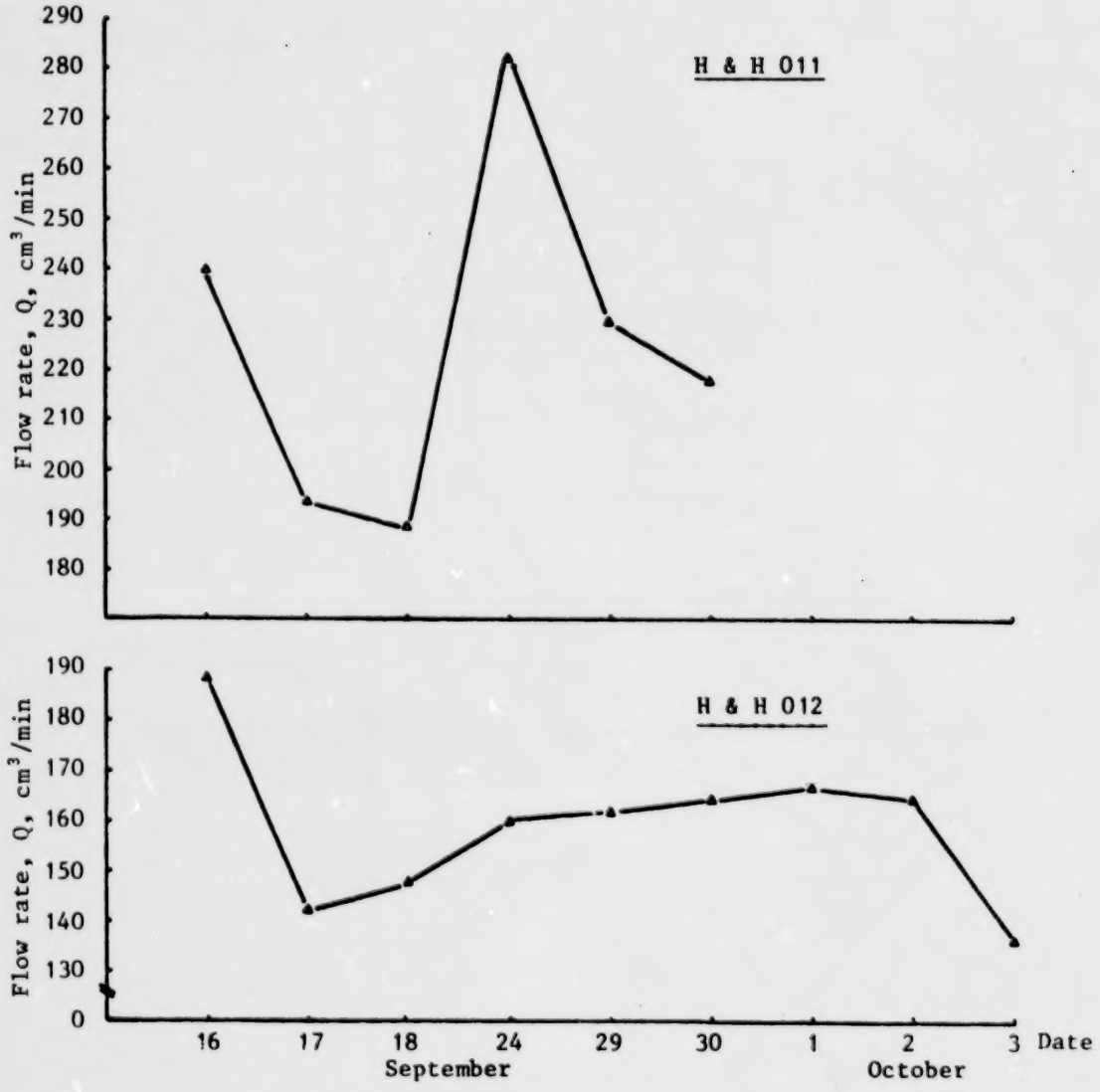



Fig. 9 - Dosimeter flow rate versus date for two H & H dosimeters: H & H 011 and H & H 012.

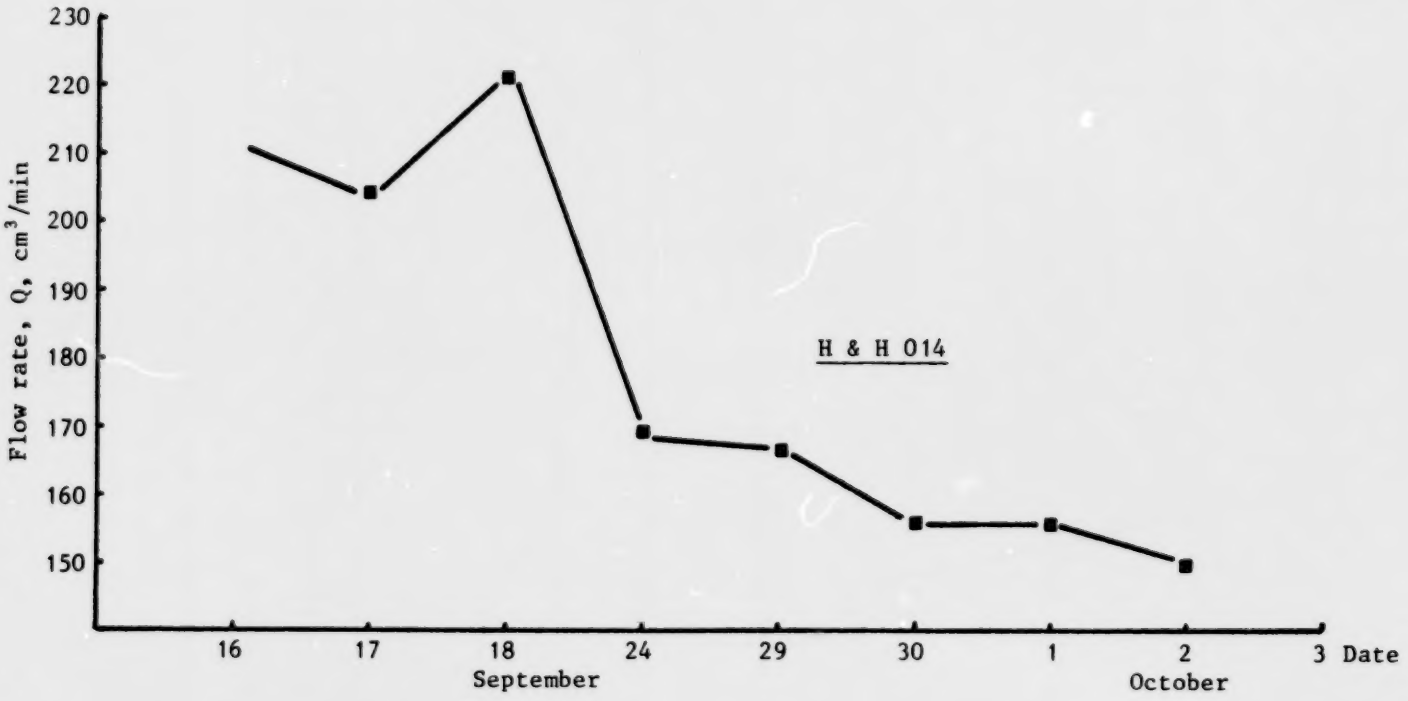



Fig. 10 - Dosimeter (H & H 014) flow rate versus date.

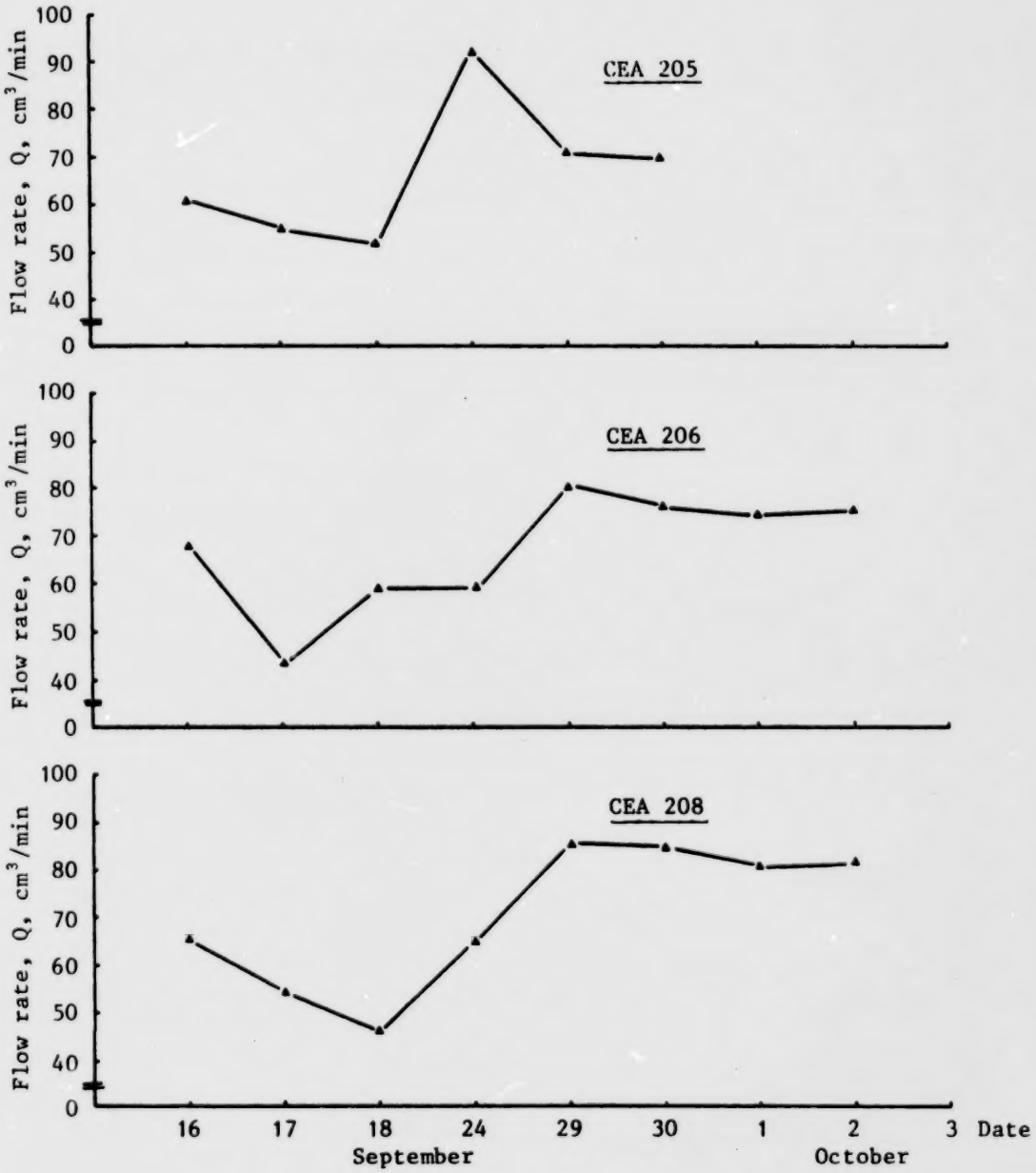



Fig. 11 - Dosimeter flow rate versus date for three track-etch dosimeters: CEA 205, CEA 206 and CEA 208.

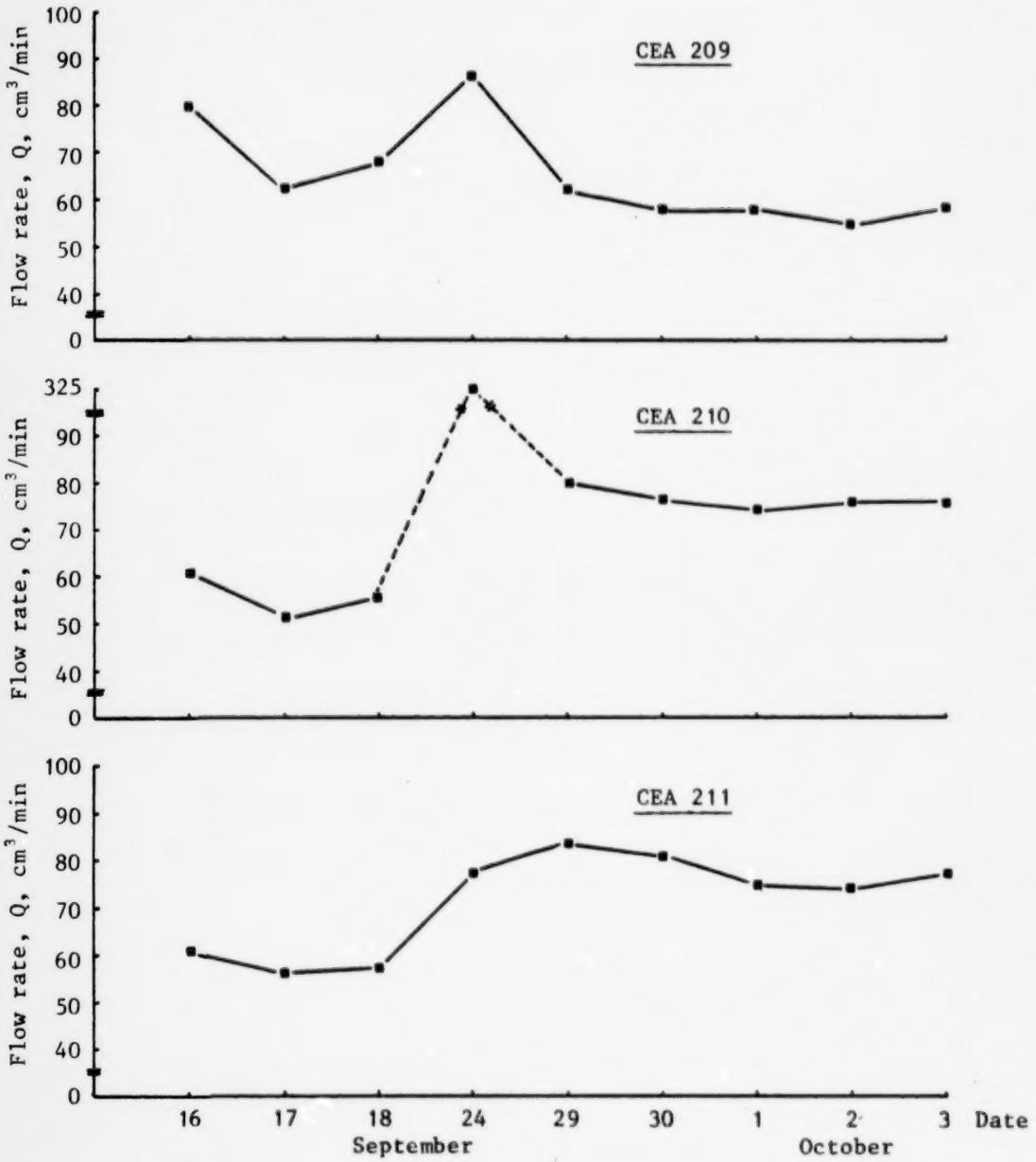



Fig. 12 - Dosimeter flow rate versus date for three track-etch dosimeters: CEA 209, CEA 210 and CEA 211.

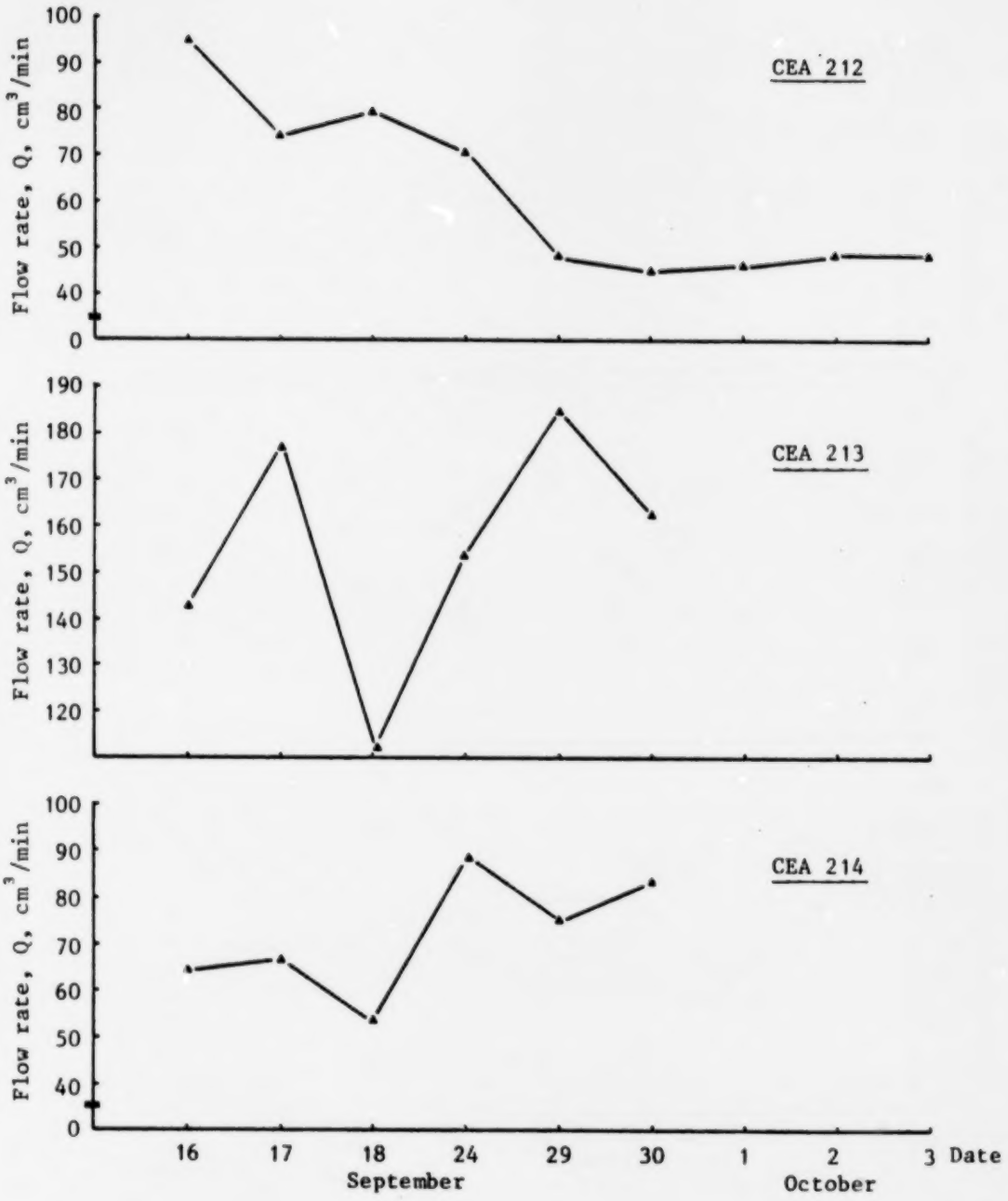



Fig. 13 - Dosimeter flow rate versus date for three track-etch dosimeters: CEA 212, CEA 213 and CEA 214.

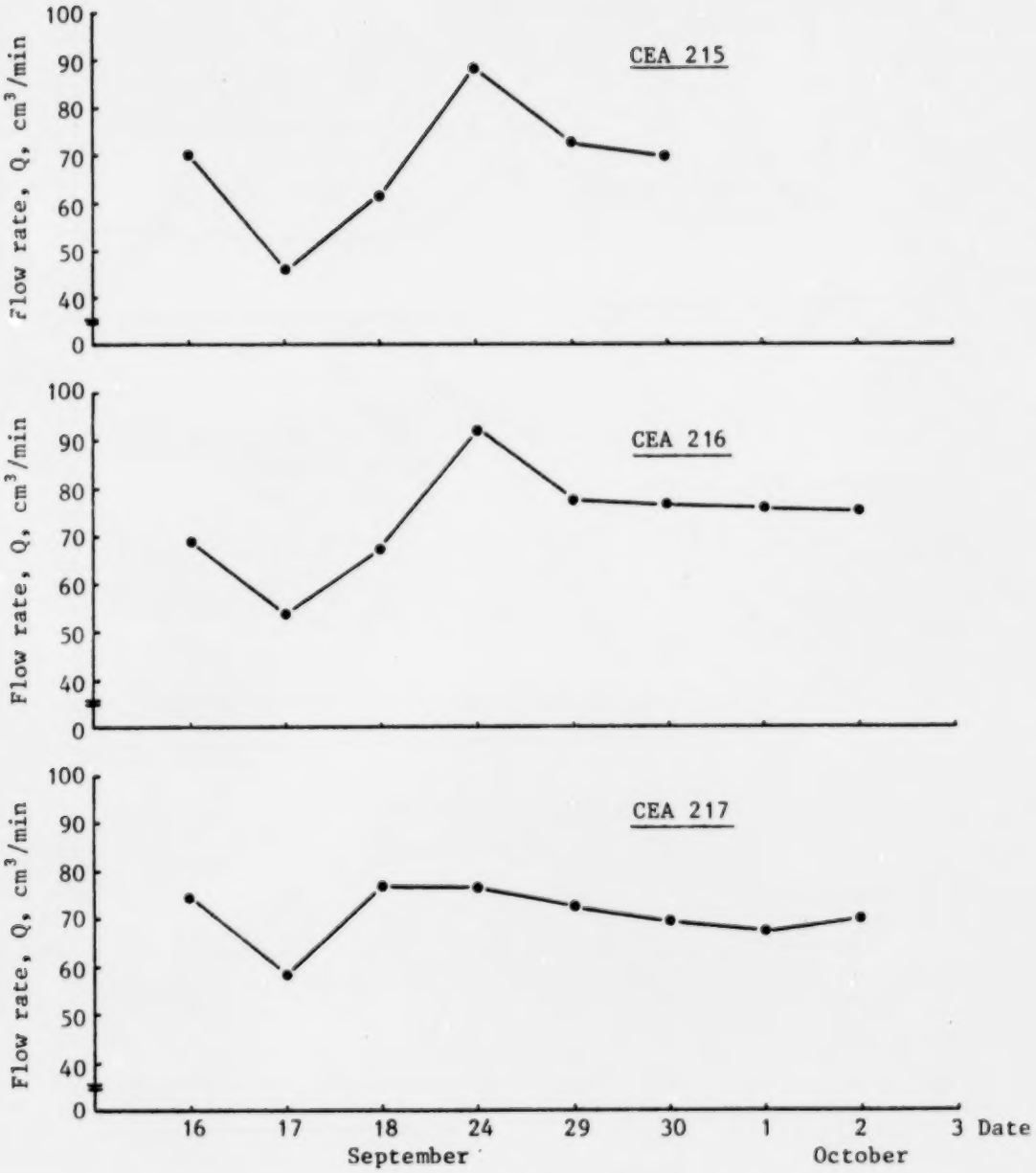



Fig. 14 - Dosimeter flow rate versus date for three track-etch dosimeters: CEA 215, CEA 216 and CEA 217.

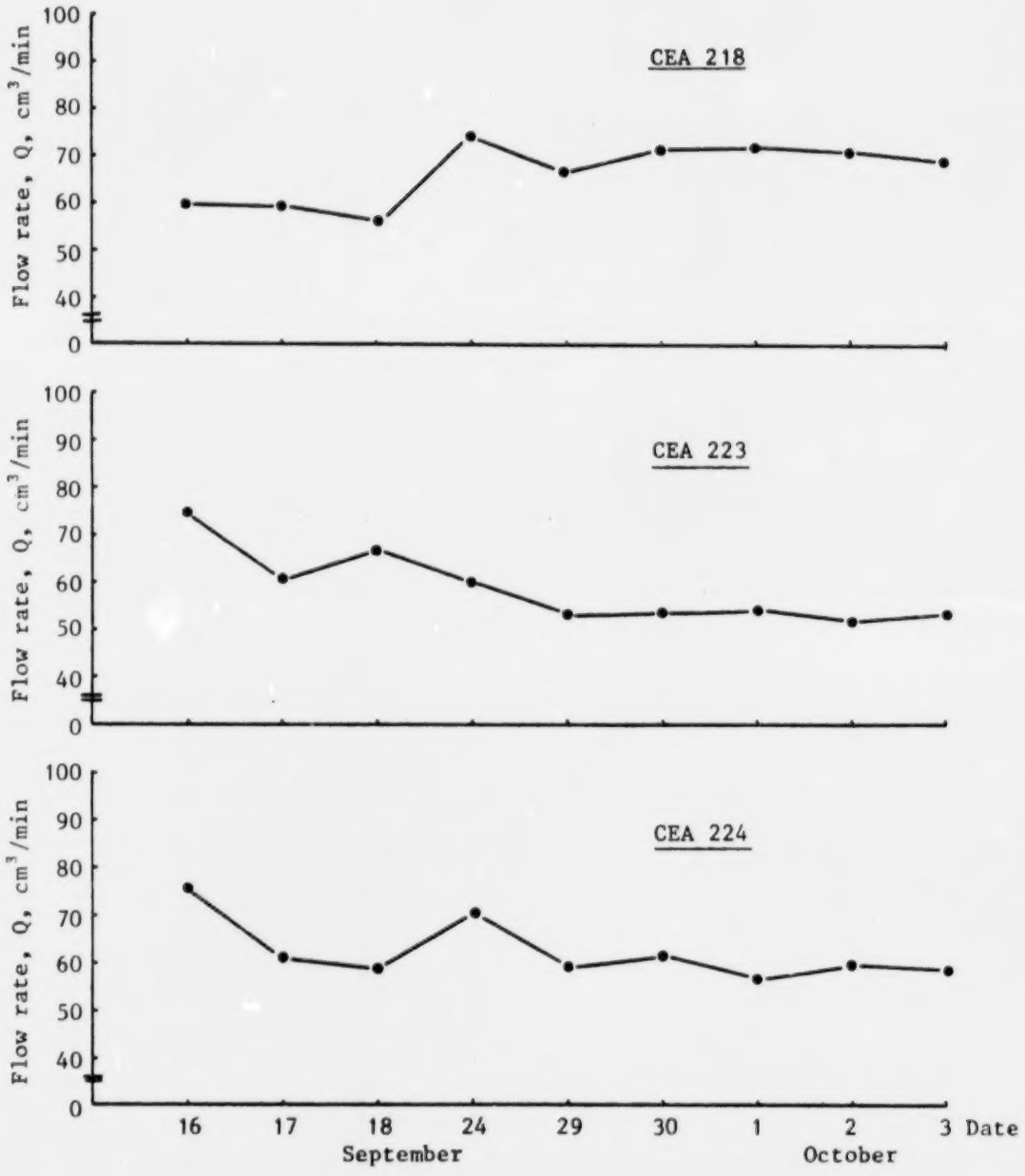



Fig. 15 - Dosimeter flow rate versus date for three track-etch dosimeters: CEA 218, CEA 223 and CEA 224.

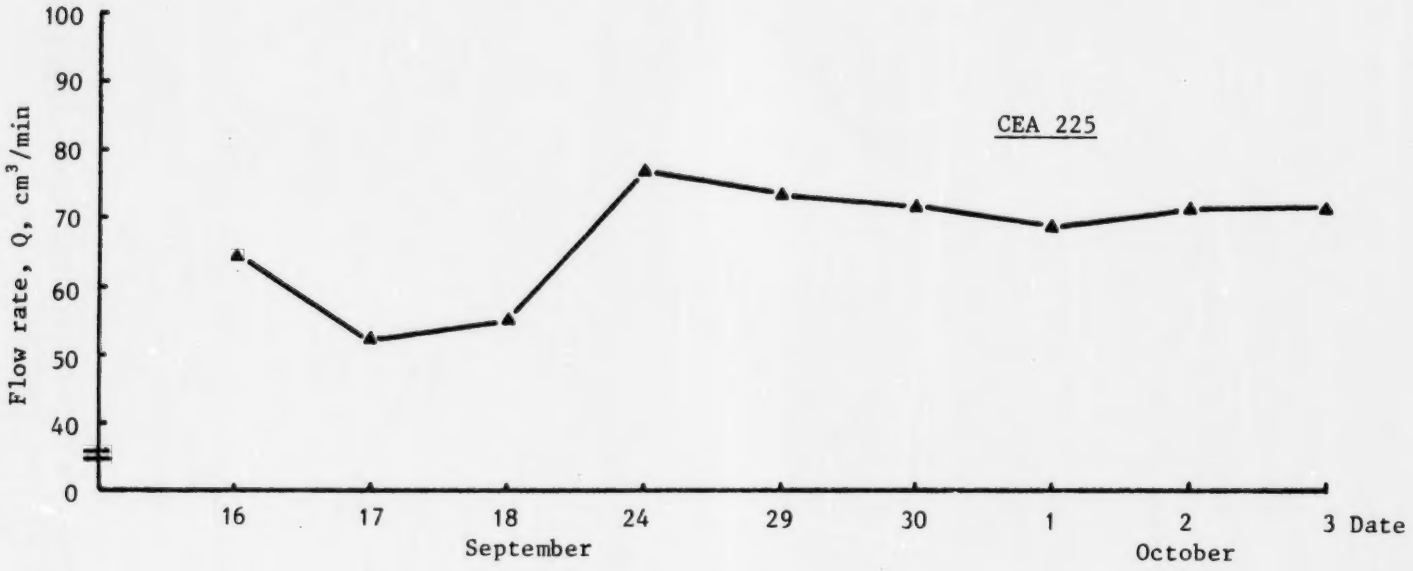



Fig. 16 - Dosimeter flow rate versus date for track-etch dosimeter CEA 225.

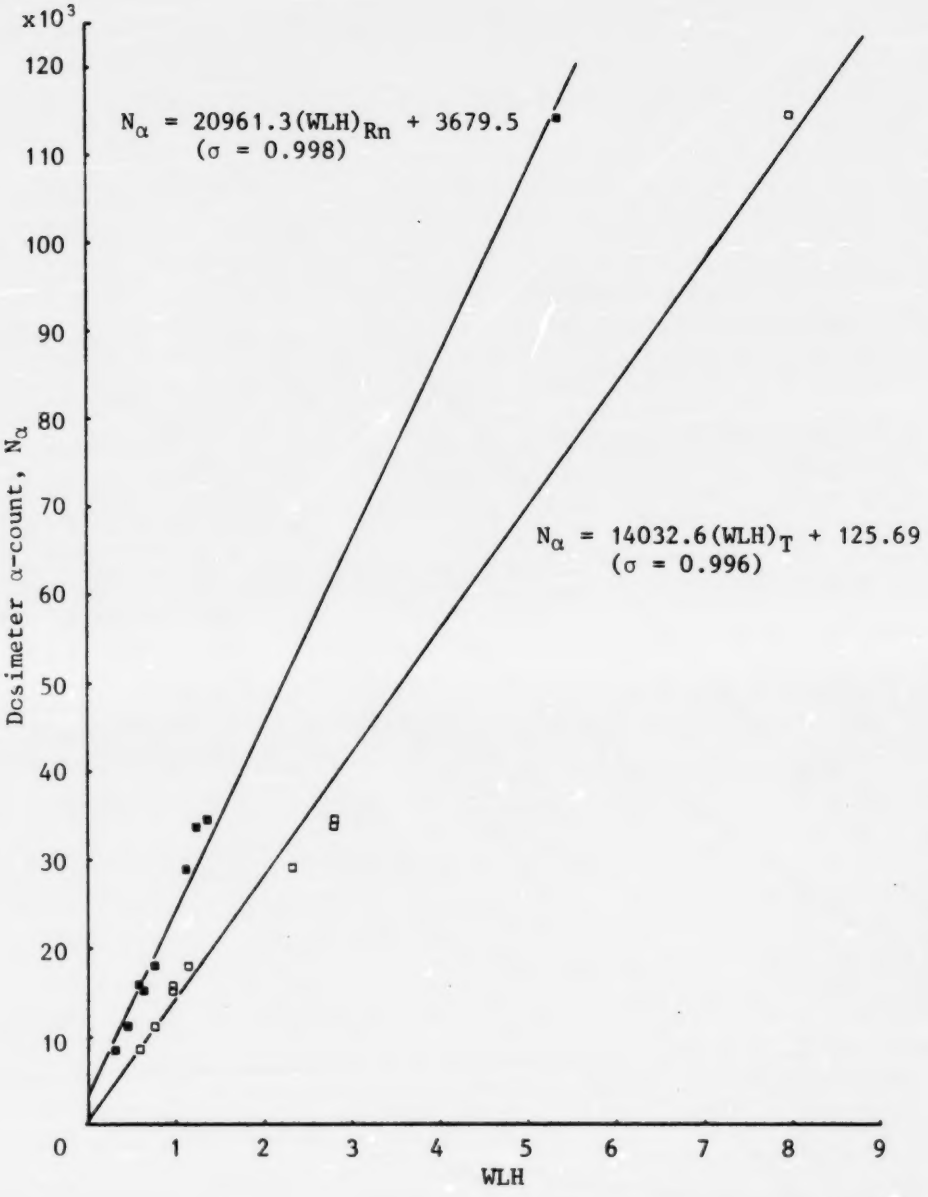



Fig. 17 - Dosimeter α-count versus WLH for α-NUCLEAR dosimeter DM008. The subindices Rn and T in WLH stand for radon daughter and total, respectively. Lines and equations obtained by linear regression analysis. σ is the correlation coefficient.

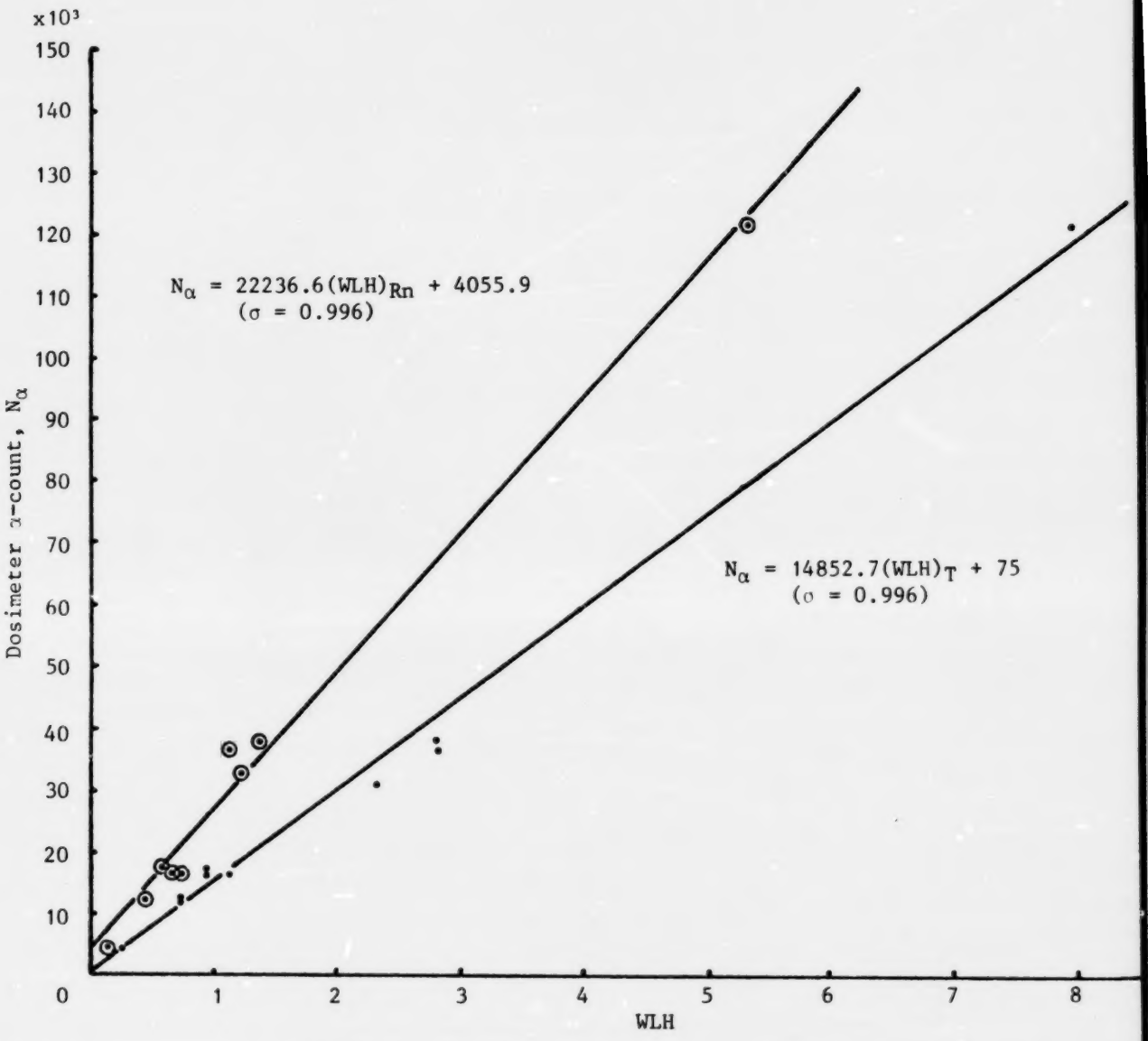



Fig. 18 - Dosimeter α-count versus WLH for α-NUCLEAR dosimeter DM012. The subindices Rn and T in WLH stand for radon daughter and total, respectively. Lines and equations obtained by linear regression analysis. σ is the correlation coefficient.

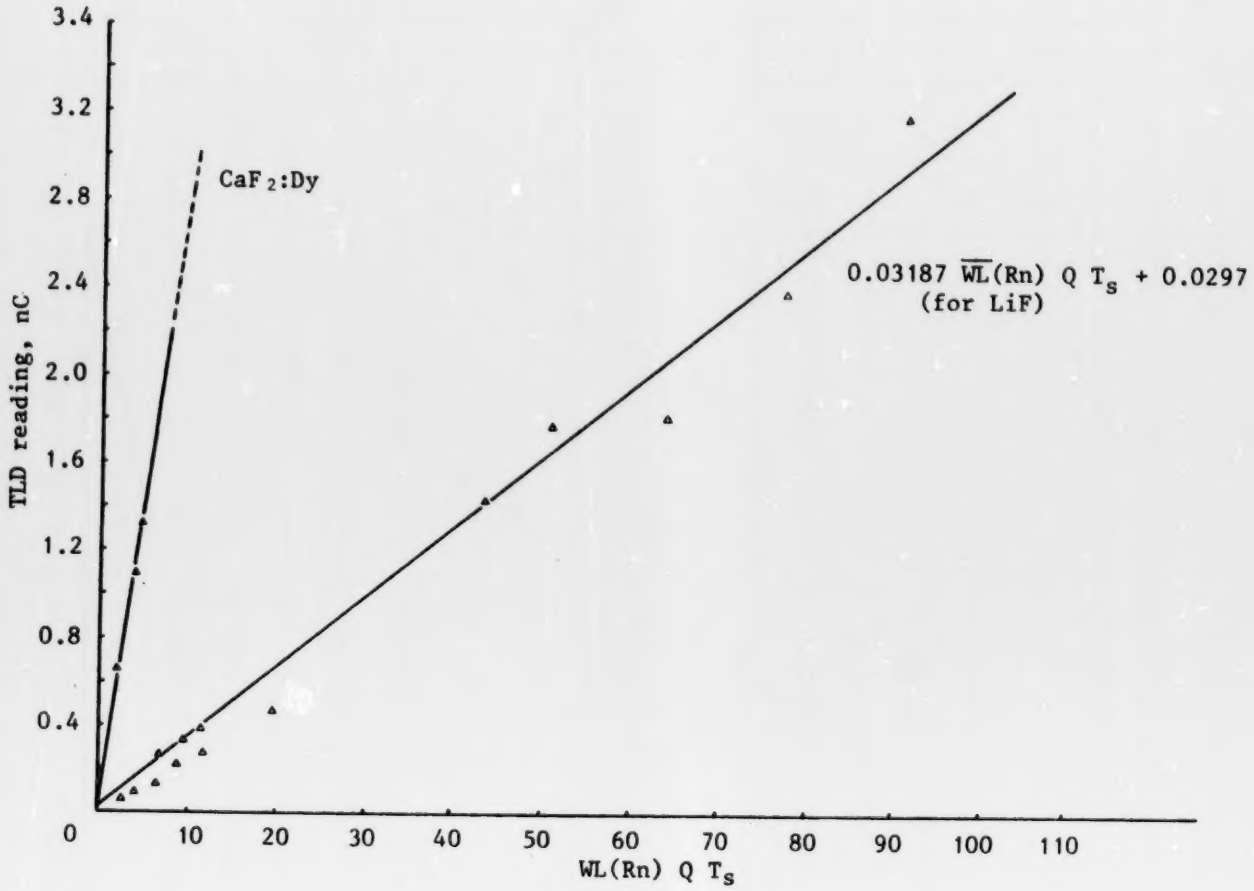



Fig. 19 - TLD reading versus WL(Rn) Q $T_S$ for the H & H dosimeters. The TLD materials used were $CaF_2$:Dy (left hand side graph) and LiF (right hand side graph). Graphs were obtained by linear regression analysis. nC stands for nanoCoulombs.

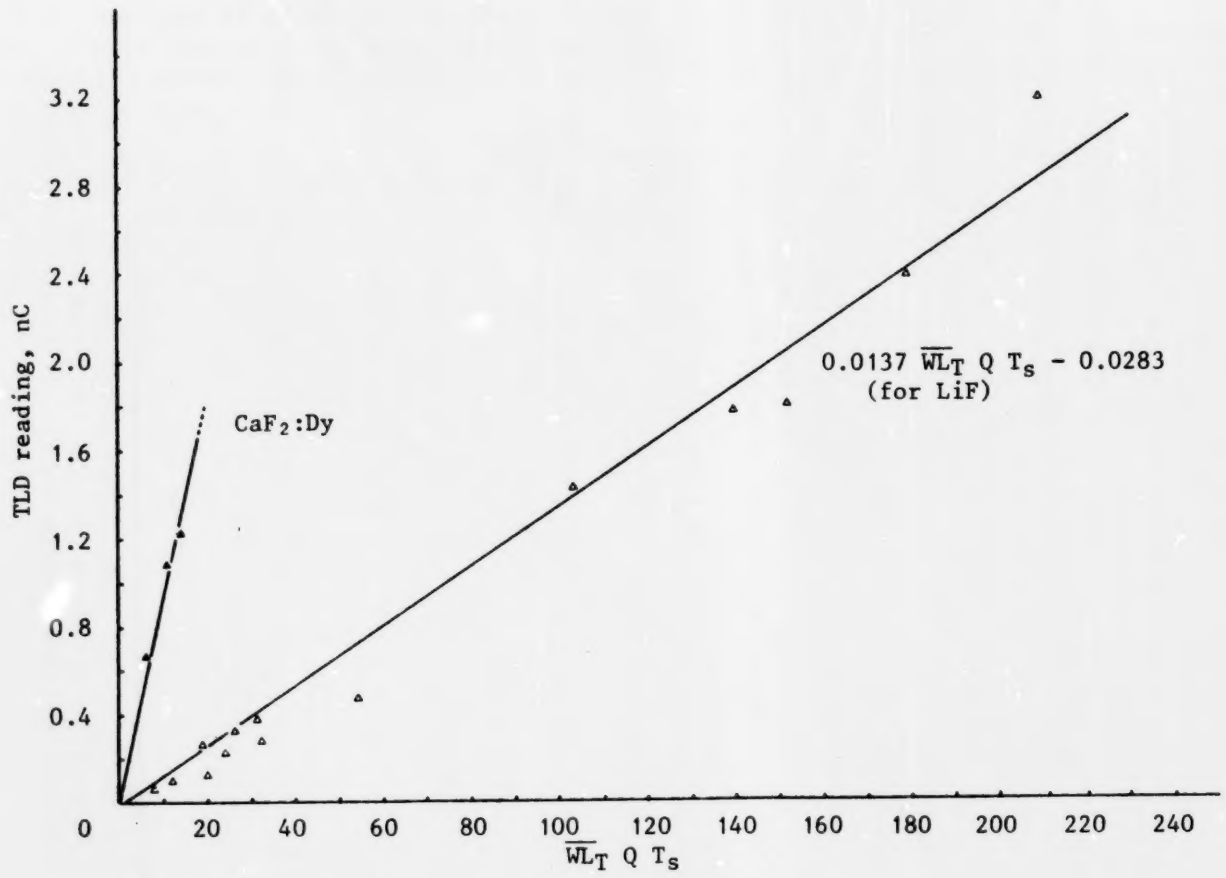



Fig. 20 - TLD reading versus $\overline{WL}_T$ Q $T_s$ for the H & H dosimeters. The TLD materials used were $CaF_2$:Dy (left hand side graph) and LiF (right hand side graph). Graphs were obtained by linear regression analysis. The symbol $WL_T$ stands for total WL, nC stands for nanoCoulombs.

Figures 21 and 22 show histograms of the frequency of occurrence for which the values of WL(Rn) and WL(Tn) as determined by the track-etch dosimeters are within a given range. The Figures show results for a 1-day, 3-day, 2-day, 4-day and 5-day test. All 16 dosimeters were used in the 1-day and 3-day tests. The 2-day, 4-day and 5-day tests were conducted as follows. Sixteen dosimeters were placed underground, out of which 4 were withdrawn after 2-days of testing. From the remaining 12 dosimeters, 8 were withdrawn after 4-days of testing, the rest (i.e., 4 dosimeters) were left for an extra day.

Figures 23 and 24 show the net TLD reading versus $\overline{WL}(Rn)V$ and $\overline{WL}_T V$, respectively, for the TLD/CAMPED dosimeters (6 units). $V(=QT_S)$ is the total volume of air sampled during a day shift. The straight lines represent the best fitted lines through the data points by linear regression analysis. The upper (lower) line was obtained using $LiF(CaF_2:Dy)$ chips.

Figure 25 gives a comparison between $\overline{WL}(Rn)$ and $N_\alpha/V$ ($\alpha$-count/L) for an $\alpha$-NUCLEAR dosimeter (DM008) for the two weeks of underground testing.

Underground meteorological conditions varied significantly from day to day for both the non-dieselized (Sept. 16, 17, 18, 24) and dieselized (Sept. 29, 30 and Oct. 1, 2, 3) sections of the mine. Significant differences were also observed between the two sites (see Fig. 1). A clear correlation of the daily average air flow and WL(Rn) and WL(Tn) is observed by comparing Fig. 1 and Fig. 5, where as expected these two variables increase with decreasing air flow. Also, as theoretically predicted (12,17), the ratio WL(Tn) decreases (increases) with decreasing (increasing) air flow. This is experimentally confirmed by comparing Fig. 1 with Fig. 6. No immediately obvious effects due to barometric pressure, temperature and relative humidity changes were observed on the radiation levels, mainly influenced by air flow changes or dosimeter performance.

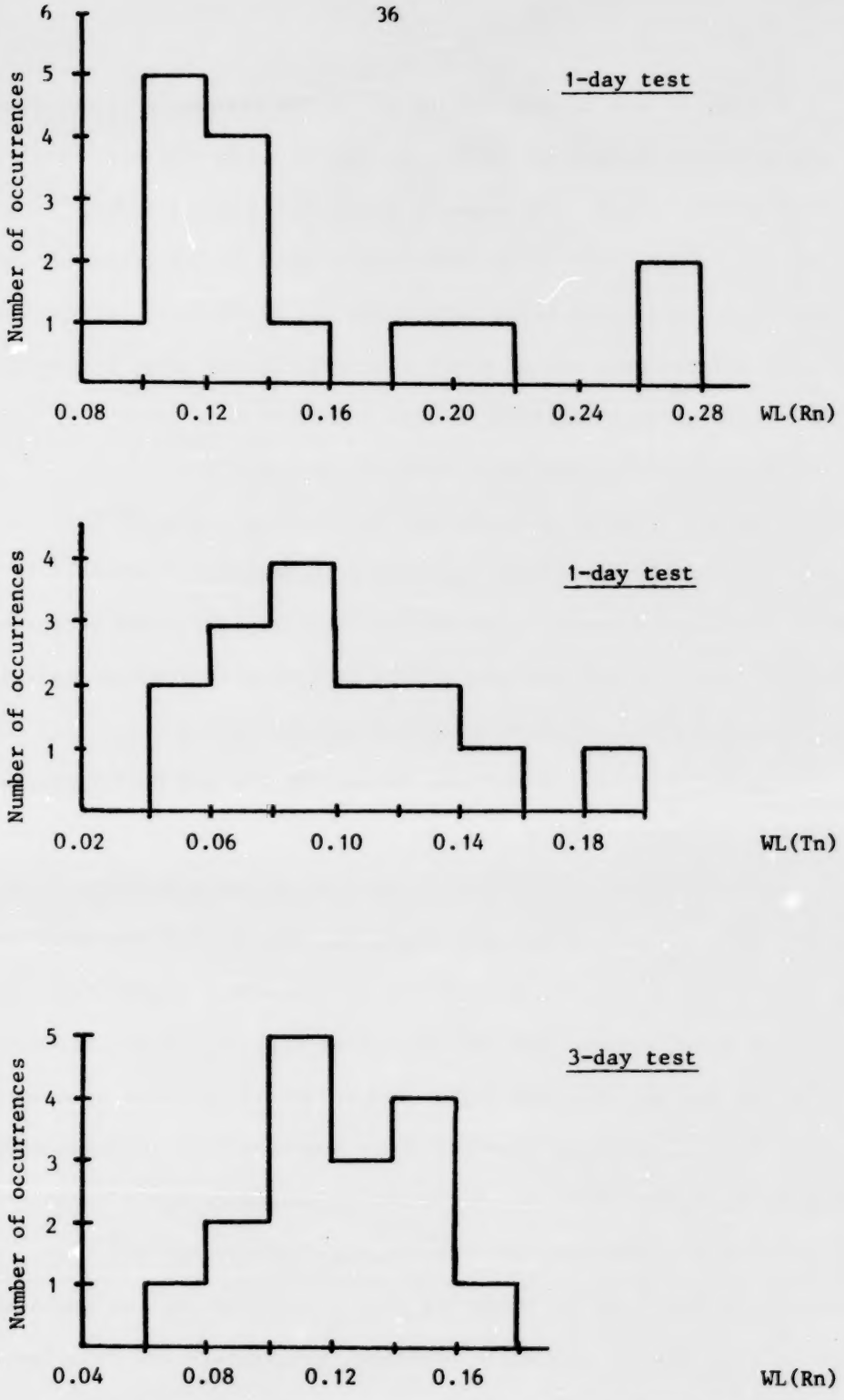



Fig. 21 - Number of occurrences versus WL(Rn) and WL(Tn) for the track-etch dosimeters for 1-day test and 3-day test. $\overline{WL}$(Rn) and $\overline{WL}$(Tn) by grab-sampling for the 1-day test was 0.17 and 0.085, respectively. $\overline{WL}$(Rn) and $\overline{WL}$(Tn) for the 3-day test was 0.13 and 0.076, respectively.

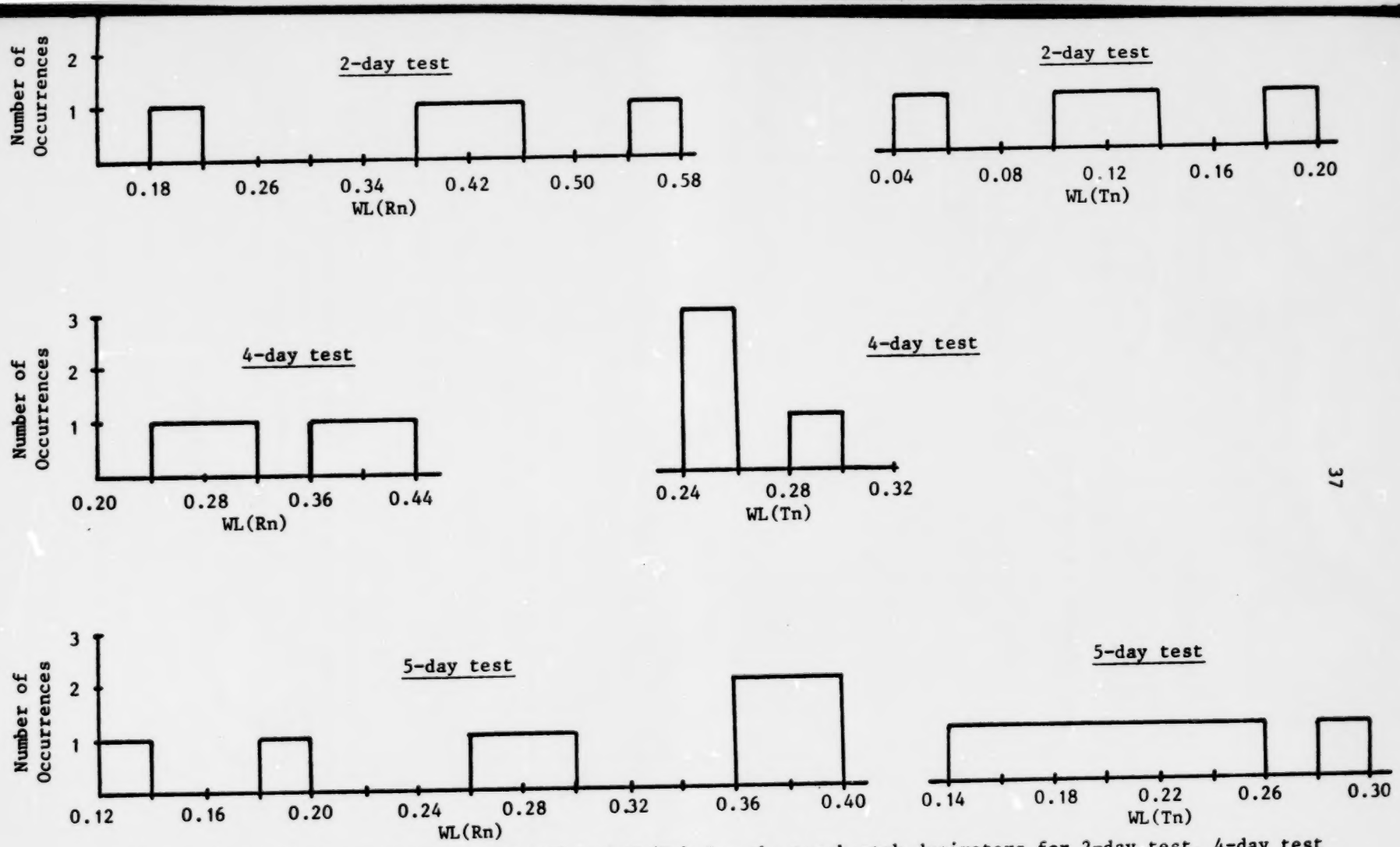



Fig. 22 - Number of occurrences versus WL(Rn) and WL(Tn) for the track-etch dosimeters for 2-day test, 4-day test and 5-day test. $\overline{WL}$(Rn) ($\overline{WL}$(Tn)) by grab-sampling for the 2-day test, 4-day test and 5-day test was 0.82 (0.47), 0.56 (0.40) and 0.5 (0.38), respectively.

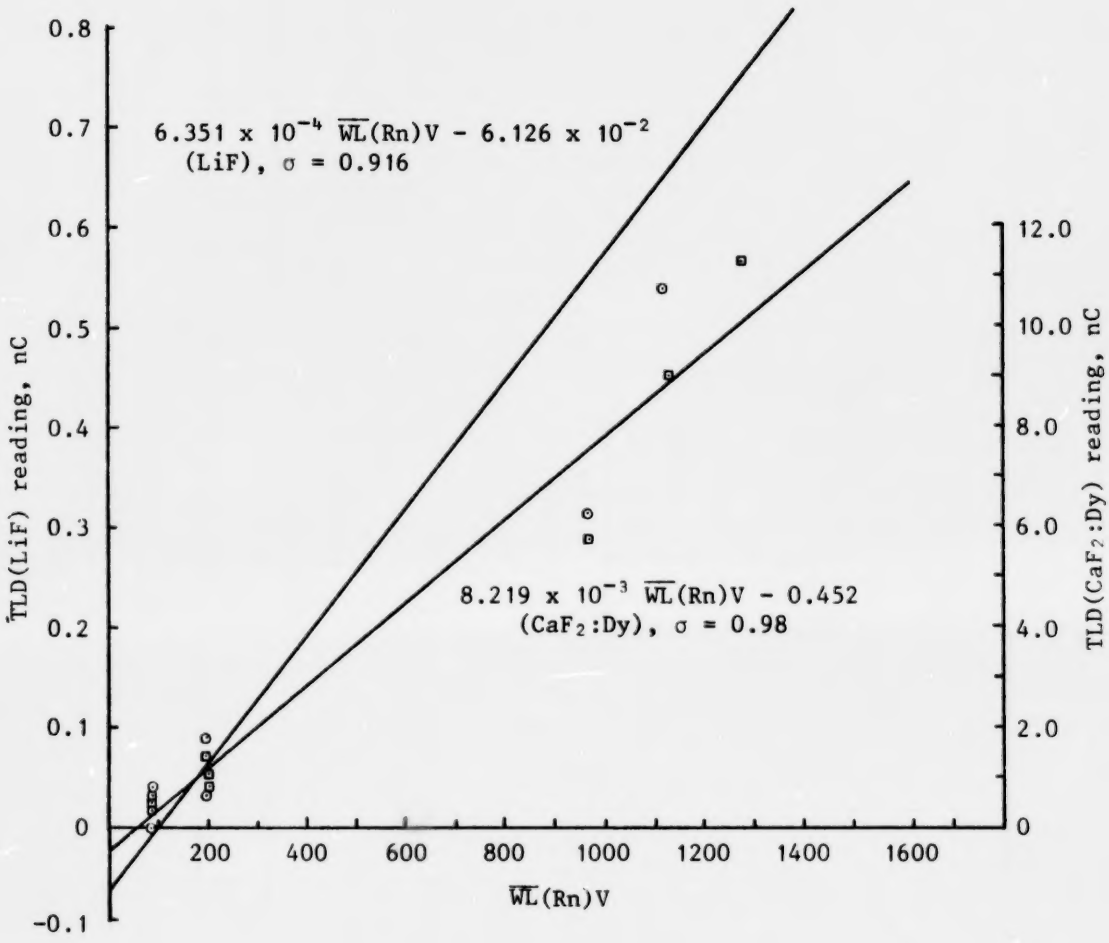



Fig. 23 - TLD reading versus $\overline{WL}$(Rn)V for the TLD/CAMPED dosimeter. V stands for total volume of air sampled. Graphs corresponding to best fitted lines, by linear regression analysis, through experimental data points (⊙ for LiF, ⊡ for $CaF_2$:Dy). σ stands for correlation coefficient, nC for nanoCoulombs.

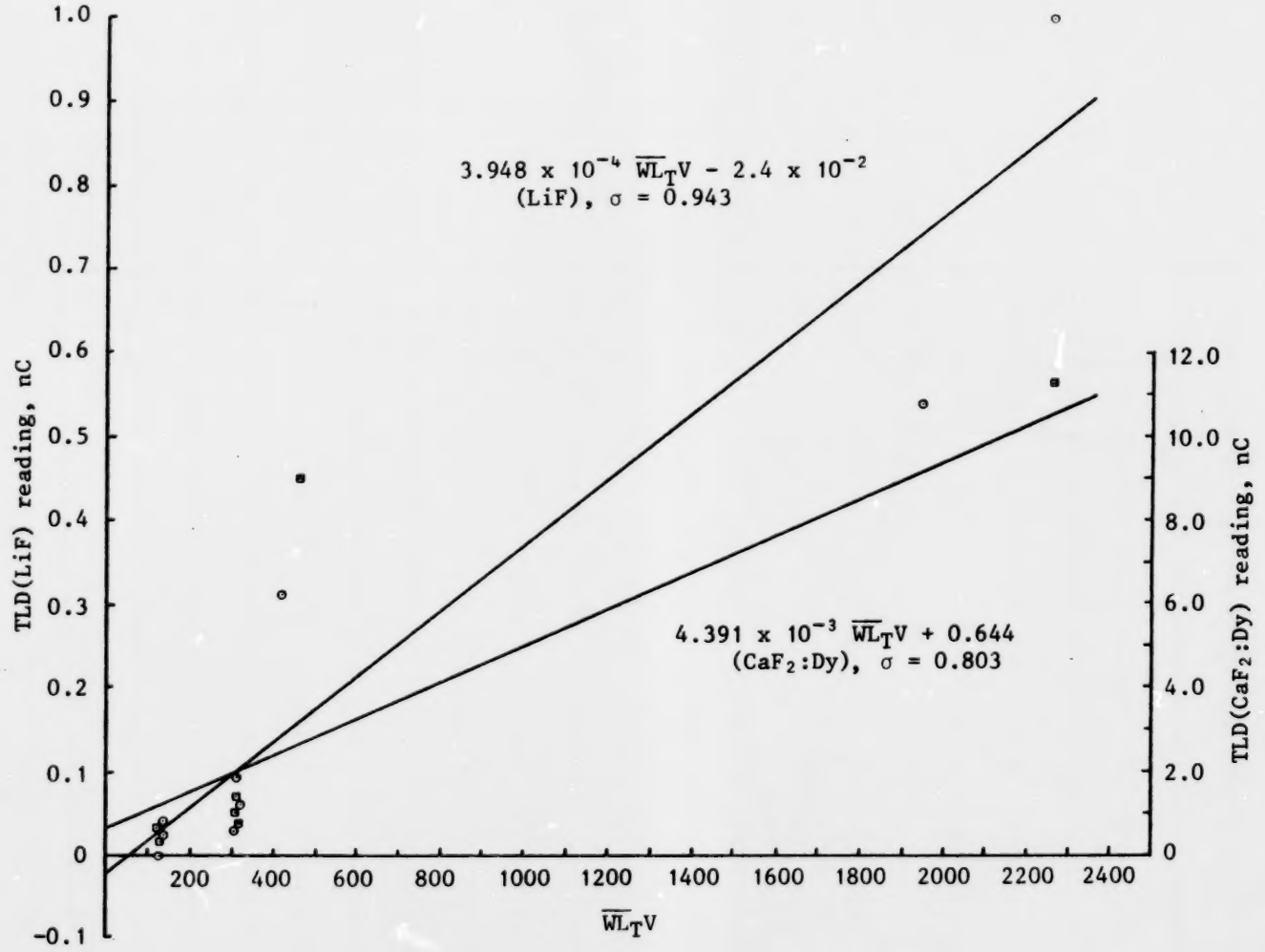



Fig. 24 - TLD reading versus $\overline{WL}_T V$ for the TLD/CAMPED dosimeters. $\overline{WL}_T$ stands for daily average total WL. V stands for total volume of air sampled. Graphs corresponding to best fitted lines, by linear regression analysis, through experimental data points (⊙ for LiF, ⊡ for $CaF_2$:Dy). $\sigma$ stands for correlation coefficient, nC for nanoCoulombs.

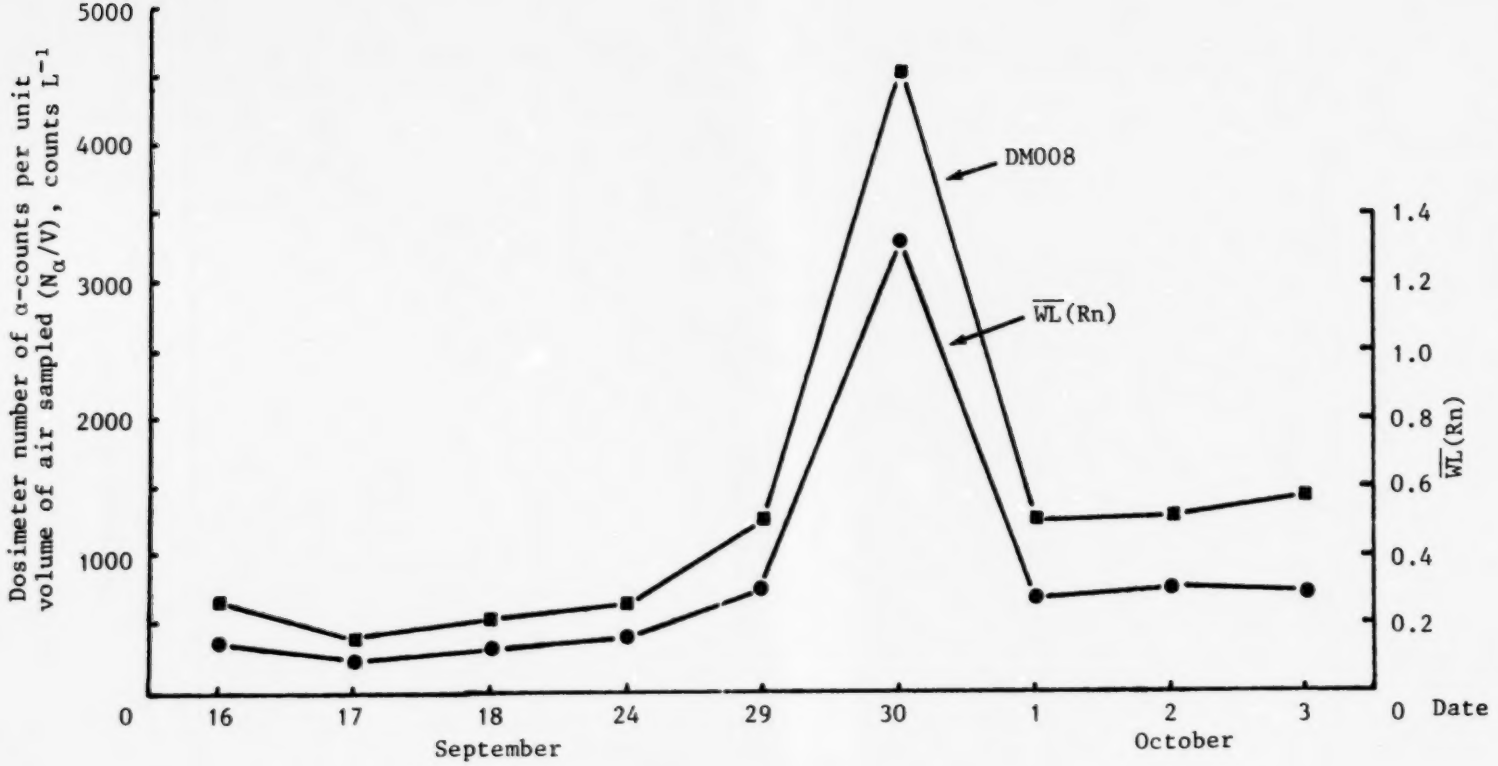



Fig. 25 - Dosimeter α-count versus date for α-NUCLEAR dosimeter DM008 (upper curve) and daily average $\overline{WL}$(Rn) by grab-sampling versus date (lower curve).

Experimental data show (see Fig. 2) that most of the measurements carried out of the ratios [RaB]/[RaA] and [RaC]/[RaA] are in the range 0.3 to 0.55 and 0.15 to 0.4, respectively. The individual measurements are plotted in Fig. 3 and show that they are within the theoretical boundaries predicted by the mine-tunnel model, the isolated model and the 'air mixing' model (12, 16,17,18). The age of air can be obtained from this graph or from Fig. 4 (15,17). The experimental data are scattered over a wide range, but most of the measurements concentrate on an area corresponding to an age of mine air approximately between 25 min and 50 min.

Although the WL(Rn) and WL(Tn) daily profiles were far from constant (large fluctuations were observed during a normal shift), their daily averages remained relatively constant at each working location over the period of time during which the experiments were carried out (see Fig. 5), except for Sept. 30 where a failure in a main ventilation fan caused a marked increase in WL(Rn) and WL(Tn). The average daily ratio WL(Tn)/WL(Rn) ranged from 0.5 to 1.25.

The flow rate measurements corresponding to the TLD/CAMPED dosimeter (not shown) remained fairly constant over the working shift (2.1 L/min) and was adjusted daily to this value. The flow rate corresponding to the two α-NUCLEAR dosimeters tested remained reasonably constant over the period of time during which the experiments lasted with variations of about ± 3% from the mean value (see Fig. 7). The flow rates corresponding to some of the track-etch detectors varied significantly from day to day. Furthermore, a wide range of flow rates for the different pumps was found (see Fig. 11 to 16). The flow rates corresponding to the H & H dosimeters varied quite markedly as shown in Fig. 8 to 10. In terms of pump performance, the TLD/CAMPED ranked first followed by the α-NUCLEAR, track-etch and finally, the H & H dosimeter. It must be emphasized that the dosimeters used, particularly the track-etch

and H & H, had been in operation for an indefinite period of time before our test. It is, therefore, possible that newer pumps would have performed better. (Note: all flow-rate measurements for each pump versus date for R.A.T.I. have been plotted - see Fig. 7 to 16 - in order to illustrate flow-rate variability. In what follows only flow-rate histograms will be shown for the other underground tests.)

The results in Fig. 17 and 18 show that within the range of underground meteorological and radiation conditions during the tests, the α-NUCLEAR dosimeters responded in a linear fashion (by linear regression analysis, with correlation coefficient $\sigma > 0.99$) to the quantity WLH where WLH, obtained by grab-sampling techniques, refers to the radon daughter WL or the total WL. The graphs permit calculation of the slope, $K_f$, to be calculated where $K_f$ is defined as:

$$K_f = N_\alpha/(WLH)_{Rn}Q \qquad \text{Eq 1}$$

The factor $K_f$ is in fact a calibration factor that can be used to obtain WL(Rn) and hence $(WLH)_{Rn}$ in any mine atmosphere, provided the underground conditions remain the same as those indicated in Fig. 1 to 7. $K_f$ for the two dosimeters did not differ by more than about 12%, i.e., 247.6 ± 25.5 for DM008 and 276.3 ± 44.1 for DM012, if the sampling time is given in hours and Q in cc $min^{-1}$. Thus, an average value of 260 ± 30 is obtained which is in agreement with previous measurements (1). The above figures can be converted to more consistent units by multiplying by the factor $\frac{1000\ ccL^{-1}}{60\ mh^{-1}} = 16.67$. Hence, the average value for $K_f$ is 4333.33 ± 500 α-count $L^{-1}$ $WL^{-1}$.

The results from the calibration of the H & H dosimeters (see Fig. 19 and 20) indicate that the $CaF_2$:Dy chips are significantly more sensitive to α-radiation than LiF. A linear relationship (by linear regression analysis) was found between TLD readings in nanoCoulombs, nC, and the product $\overline{WL}(Rn)$ x

$T_S \times Q$ or $\overline{WL}_T \times T_S \times Q$. As many more measurements were conducted with LiF, the sensitivity of the dosimeters using this kind of chip could be much better estimated. The sensitivity of the H & H dosimeter is defined as:

$$\frac{nC}{(WLH)_{Rn}\ Q\ T_s} \qquad \text{Eq 2}$$

where nC represents the net TLD reading in nanoCoulombs. This reading is obtained by subtracting the shielded TLD chip reading from the unshielded TLD chip reading. The sensitivity of the H & H dosimeter for WL(Rn) using LiF chips was estimated to be $1.5 \times 10^{-3} \pm 4.7 \times 10^{-4}$nC $WLH^{-1}$ $L^{-1}$, a factor that can be used to determine WL(Rn) in unknown mine atmospheres.

Track-etch dosimeters gave a wide range of values for WL(Rn) and WL(Tn) as obtained according to standard procedures recommended by the CEA. Substantial disagreement was found between the results obtained with different dosimeters under identical environmental conditions (see Fig. 21 and 22) placed in the same general location and within a relatively small area (ca. 60 cm x 60 cm). A 1-day test and a 3-day test were conducted with the 16 dosimeters available in the non-dieselized area of the mine, followed by a 2-day, 4-day and 5-day test in the dieselized area of the mine with a limited number of dosimeters, i.e., 4, 8 and 4 dosimeters, respectively. Better agreement was found for the 1-day and 3-day tests than for the other tests, a fact which is ascribed to the anomalously higher than normal values of WL(Rn) and WL(Tn) on Sept. 30th, that lasted for several hours due to failure of a main ventilation fan. Other sources of error, common to other dosimeters as well, will be discussed below.

The results of the TLD/CAMPED dosimeters show that, as for the case of the H & H dosimeters, the sensitivity of CaF :Dy chips is noticeably higher (about one order of magnitude) than that corresponding to LiF, however, the results are greatly scattered in both cases as shown in Fig. 23 and 24. The

reason for the scattering of the data is not fully understood, but one reason might be the quite unfavourable mechanical configuration and geometry of the sampling head (impactors, etc.) which although necessary for effective dust collection in the respirable size range (1 μm to 10 μm) can cause considerable plate-out of the decay products of radon and thoron. As plate-out depends upon the concentration, size distribution and kind of aerosols present, quantities which depend upon environmental conditions and mining operations, the determination of plate-out is rather difficult.

A comparison of the sensitivity of the TLD/CAMPED and the H & H dosimeters show that the latter are considerably more sensitive (about 50 times) to α-radiation than the former in spite of the much higher pump flow-rate of the TLD/CAMPED sampler, i.e., 2.1 L/min, as compared with approximately 0.1 L/min for the H & H dosimeter. The reason for this lies in the more favourable geometry of the TLD chips in relation to the sampling head. Thus, while in the H & H dosimeters the unshielded chip is located about one mm from the filter and exactly above its centre, in the TLD/CAMPED the chips sit on a conical-shaped piece resting on the filter holder containing the filter. The TLD chips are, therefore, obliquely oriented, off-centre and about 8 mm from the filter.

Figure 25 illustrates the advantages of a dosimeter such as the α-NUCLEAR prototype which enables daily readings to be made as opposed to other dosimeter prototypes more readily designed to be read far less frequently, e.g., monthly. The latter dosimeters provide radiation levels averaged, i.e., smoothed-out, over long periods of time. A dosimeter prototype which enables fast reading permits anomalies in the ventilation system, radiation levels and other important items to be detected and hence remedial action to be undertaken.

## R.A.T.2 - PERSONAL DOSIMETRY AND LONG-TERM CALIBRATION TEST: RESULTS AND DISCUSSION

Three further tests were carried out at Rio Algom. The first test (R.A.T.2) extended from Feb. 2nd to Feb. 20th, 1980. The results of this test are presented here. Except for three dosimeters, the rest of the dosimeters were used for personal dosimetry. The three dosimeters consisted of an α-NUCLEAR dosimeter (DM008), a track-etch dosimeter (No. 225) and a H & H dosimeter, and were used for long-term calibration purposes (i.e., site dosimetry). These dosimeters were placed in Shaft No. 1 exhaust where WL(Rn) measurements were conducted twice daily: one shortly after placing the dosimeters in place and another shortly before removing them. The dosimeters sampled exhaust air for a minimum of 7 hr daily. The remaining dosimeters were assigned to miners working regular day-shifts.

Personnel at the Ventilation Department of Quirke II were responsible for assigning and delivering the dosimeters to underground workers and for picking up the dosimeters when the workers returned to surface at the end of the shift. They were also responsible for conducting daily flow-rate measurements, reading the α-NUCLEAR dosimeters, changing the α-NUCLEAR filters, and carrying out WL(Rn) measurements at the Shaft No. 1 exhaust. Changing of filters and processing and reading of the other dosimeters as well as the analysis of all data collected during the test was the responsibility of CANMET staff. This work arrangement remained essentially the same for the rest of the underground tests at both Rio Algom and Denison Mine.

Because of Rio Algom staff shortages, few radiation and meteorological measurements were carried out in the underground areas of interest, namely locations where miners carrying dosimeters were working. Thus, comparison of dosimeter data and the few grab-sampling data available was not attempted. Thus, this test was mainly aimed at determining: a) the effect of diesel

particulates, dust, oil and water mist, and other air contaminants, on the dosimeters pump flow-rate; b) the long-term reliability of the pumps; and c) the long-lived radioactive dust. Item (a) is also relevant as the dosimeter reading (e.g., track-etch and H & H) is affected by the deposition on the filter of a layer of air contaminants which increases the absorption of α-particles. The R.A.T.2, and the following tests, also served to indicate the response and attitude of miners towards the use of the dosimeters, and their preference towards any particular prototype.

Miners seemed to prefer the α-NUCLEAR dosimeter over the track-etch dosimeter, which was their second choice, as this prototype combined the battery, caplamp and the dosimeter in one unit, thereby eliminating the need for carrying an extra piece of instrumentation, i.e., the dosimeter itself. (Note: the track-etch and H & H dosimeters are autonomous systems, i.e., they carry their own power supply.) The miner's preference was presumably based on simplicity of design and aesthetic reasons.

Several practical and technical difficulties were encountered in the use of the dosimeters. The performance of the H & H pumps was poor, the track-etch dosimeter 'handle' did not fit the miner's belt, and a new larger handle had to be designed for the dosimeter as the original handle only fitted the battery belt, a place where the miners refused to wear the dosimeters.

The problem with the α-NUCLEAR dosimeters was far more serious; the power pack, i.e., regular miner's caplamp battery, was not capable of maintaining the miner's caplamp in proper operating condition during a normal working shift after a few days of routine underground operation. The symptoms observed during the α-NUCLEAR underground test were as follows. After the first 3-days of satisfactory underground operation, a noticeable dimming of caplamp light was observed during the fourth-day shift which became worse as the working

shift progressed. Eventually the caplamp would cease to function on the fourth or fifth day of operation. This pattern repeated itself every week indicating that full battery charge was realized over the weekend, but full charge of the battery did not take place overnight which lead first to caplamp failure and eventually to erratic pump behaviour.

In order to investigate this problem further, the dosimeters were withdrawn from underground and a 2-week laboratory test was conducted at the Elliot Lake Laboratory (ELL), closely reproducing the procedure followed during the underground test, as follows. The dosimeters were charged overnight and operated for 8½ hr daily, i.e., the glass fibre sampling filters were changed daily and the sampling pumps, electronic circuitry and caplamps were turned on for 8½ hr. After the sampling period, the caplamps were turned off, the batteries put on charge and the dosimeters plugged into the reader. An immediate reading was taken and the reader was programmed to take another reading 4 hr after the end of the sampling period. This cycle was repeated daily. During the 2-weeks of the laboratory tests, everything seemed to function well. The caplamps were operating properly, α-readings were as expected, and the pump flow-rates were fairly constant. Environmental conditions were 20-22°C ambient temperature and 60-80% relative humidity.

Taking into account that no filter loading took place during the underground test (the filter was changed daily and no excessive amounts of particulates were present which could affect pump performance) and that the performance of the dosimeters was satisfactory during laboratory controlled conditions, it must be concluded that the harsh underground environmental conditions (e.g., lower temperature and higher relative humidity than in the laboratory test) must have adversely affected the dosimeter's power supply. There are other reasons, in addition to environmental factors, that might

affect the performance of the dosimeters including the lack of full overnight charge recovery of the dosimeter's power supply. This could be due to:

1. Dosimeter electronics consuming excessive power when plugged into the reader;
2. Battery charger supplying too low a line voltage for optimum operation, thus delivering charge to the battery at a lower rate than necessary to fully charge it overnight;
3. Excessive dosimeter power consumption during regular operation.

Item (2) was suspected, and in fact it was found that presumably because of line overloading, the battery charger at the mine site was being supplied by 110 V instead of 117 V. Item (1) could not be established. However, item (3) was a definite factor as the power requirements of the sampling pump and the electronic circuitry were about twice that originally intended for the final dosimeter prototype - not yet available at the time of writing this report - and, although this did not seem to affect the dosimeter under laboratory conditions, it did affect it under underground conditions, compounded with low battery charger capacity due to insufficient line voltage.

The α-NUCLEAR dosimeters were used underground for almost 2-weeks followed by the 2-week laboratory test at the ELL. After that the dosimeters were sent back to Rio Algom for further observation on surface, followed by two or three days underground testing. As the dosimeters developed the same symptoms, indicated above, they were withdrawn from the underground tests altogether.

Some of the data collected during the present test are given below. Because the track-etch and H & H dosimeters were read only once, i.e., after completion of the test, comparison between grab-sampling data (Shaft No. 1 exhaust) and dosimeter reading for these two dosimeter prototypes is done at

the end of Rio Algom tests, and hence includes the results of the three tests. This way, a more coherent and representative picture of the dosimeters' performance can be obtained. Some α-NUCLEAR data are also included.

Figures 26 to 29 give histograms of the track-etch and H & H pump flow-rates versus occurrence or number of events, i.e., number of times the flow-rate of a given pump is within a certain range. No histograms for the α-NUCLEAR dosimeters have been included as not enough data are available to compare with other dosimeters.

Figure 30 gives, respectively, histograms of WL(Rn), WL(Tn) and the ratio WL(Tn)/WL(Rn) as measured by the track-etch detectors.

Table 3 summarizes flow-rate data pertaining to all dosimeters tested.

Table 4 gives radiation data obtained by the α-NUCLEAR and H & H dosimeters.

Fluctuations of up to 30% or more in flow-rate were not uncommon for the track-etch dosimeters. Flow-rate variations of up to 100% were observed for some H & H dosimeters, while fluctuations of less than approximately 15% were measured for the α-NUCLEAR dosimeters (see Fig. 26 to 29).

The WL(Rn) and WL(Tn), as determined by the track-etch dosimeters, in the areas where the personal dosimetry test was conducted, showed a large spectrum of values from 0.06 to 0.26 for WL(Rn) and from 0.08 to 0.26 for WL(Tn). The ratio WL(Tn)/WL(Rn) was mainly between 0.6 to 1.2, with a maximum of about 0.6 to 0.8 (see Fig. 30). Results from a reduced number of α-NUCLEAR dosimeters obtained during the limited time of field operations are shown in Table 4. This table also gives data regarding the H & H dosimeters. As with the other dosimeter prototypes, a specific H & H dosimeter was assigned to site dosimetry (Shaft No. 1 exhaust). However, the instructions to the personnel responsible for delivering the instruments were misunderstood and

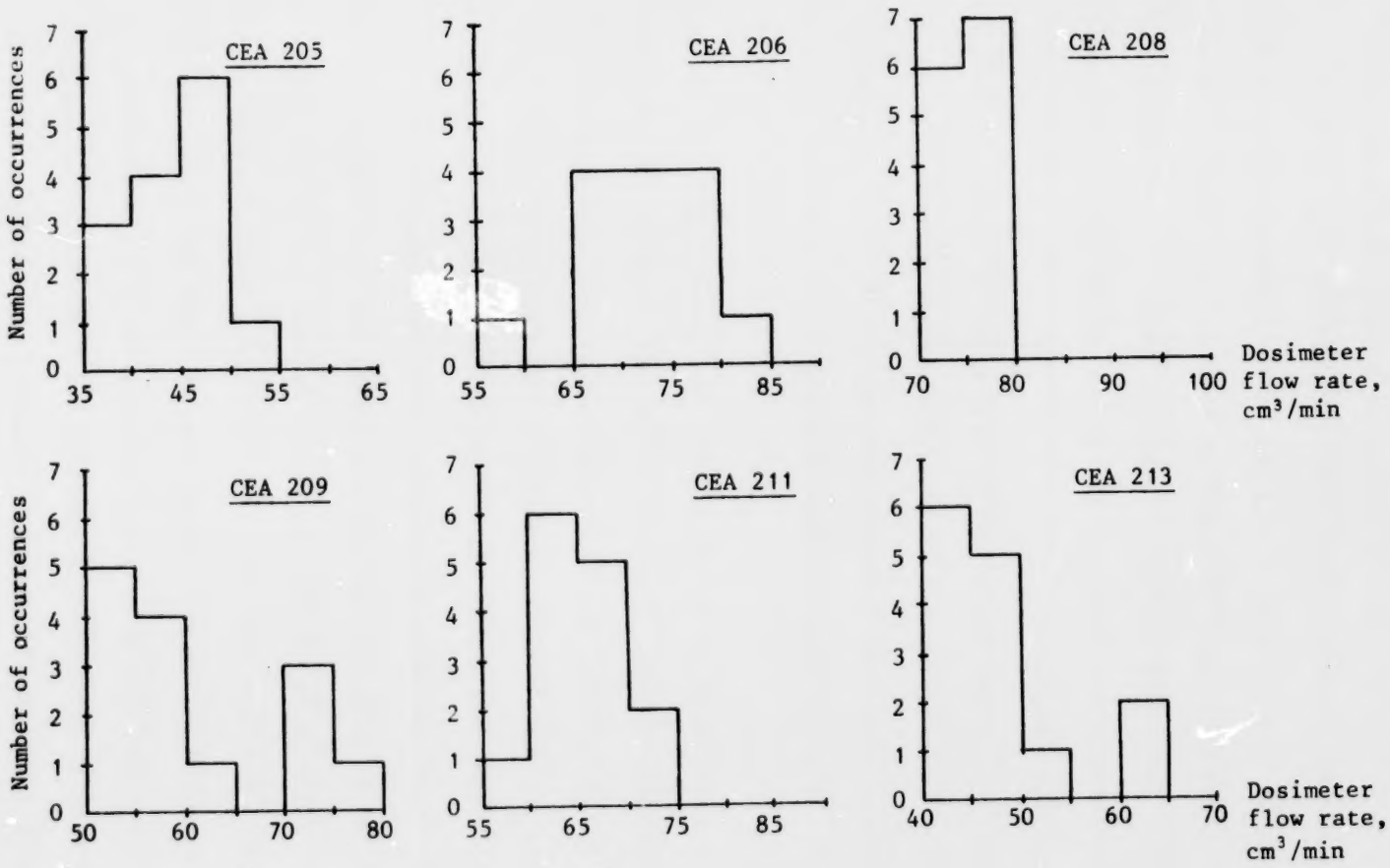



Fig. 26 - Number of occurrences versus flow rate for track-etch dosimeters CEA 205, 206, 208, 209, 211 and 213.

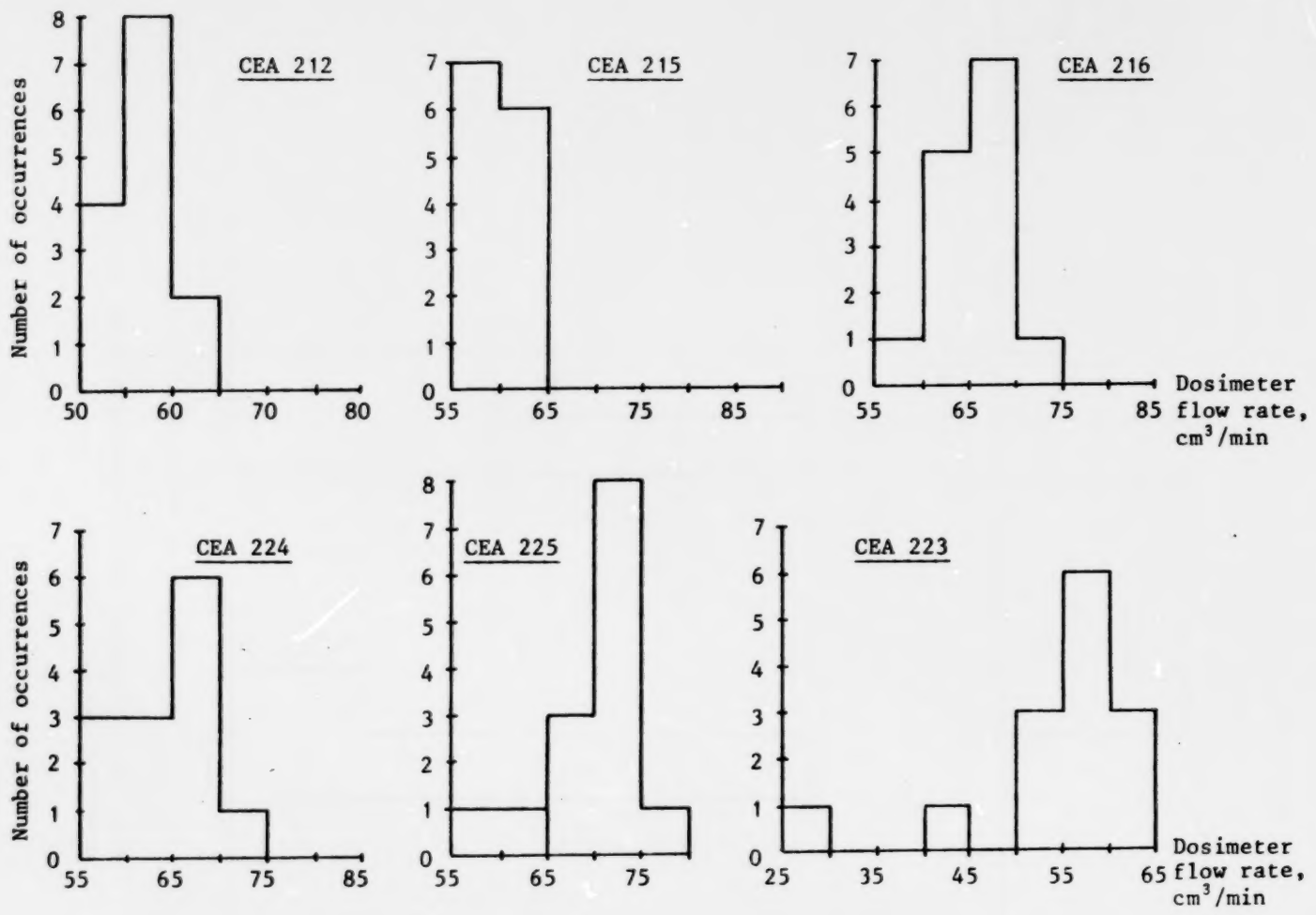



Fig. 27 - Number of occurrences versus flow rate for track-etch dosimeters CEA 212, 215, 216, 224, 225 and 223.

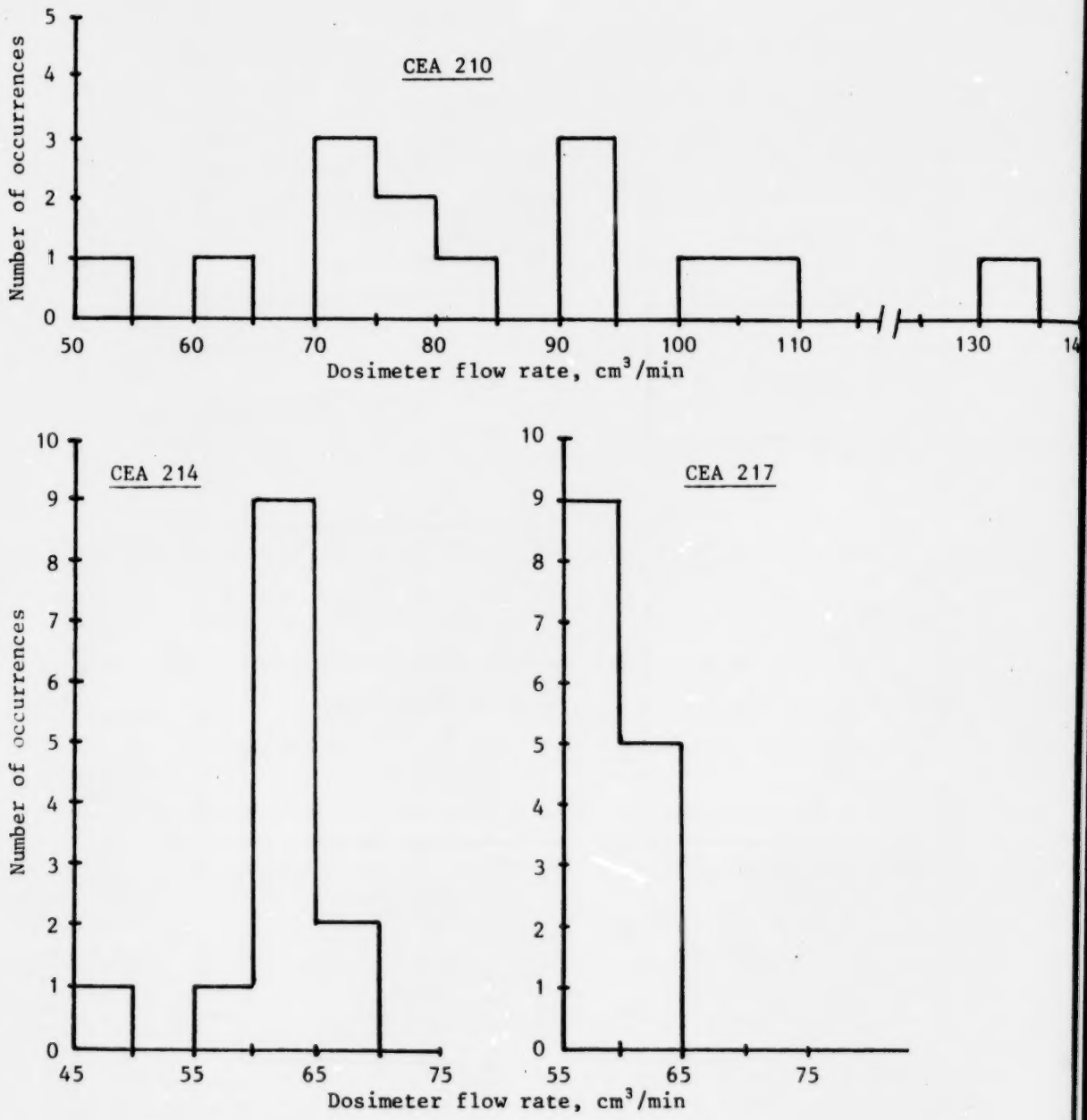



Fig. 28 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 210, 214 and 217.

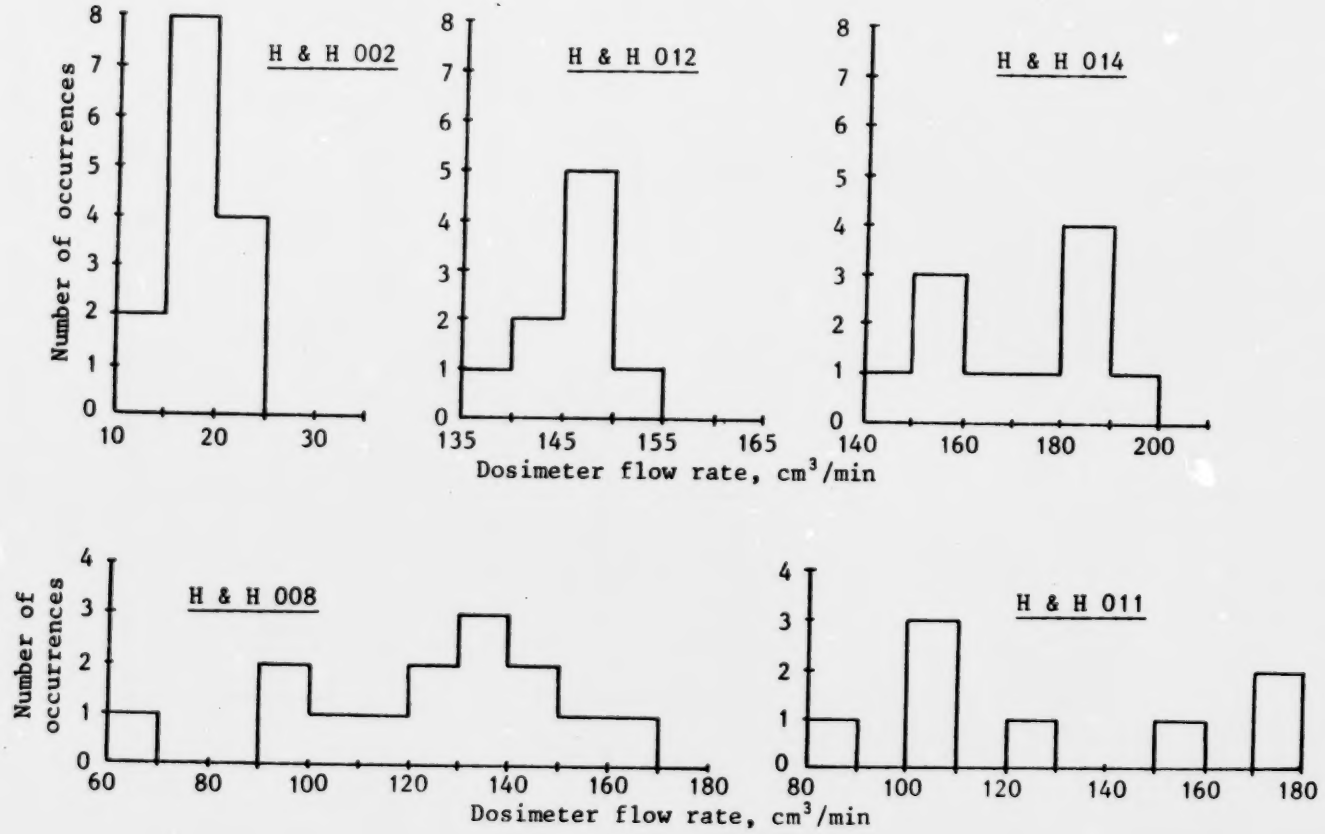



Fig. 29 - Number of occurrences versus dosimeter flow rate for H & H dosimeters H & H 002, 012, 014, 008 and 011.

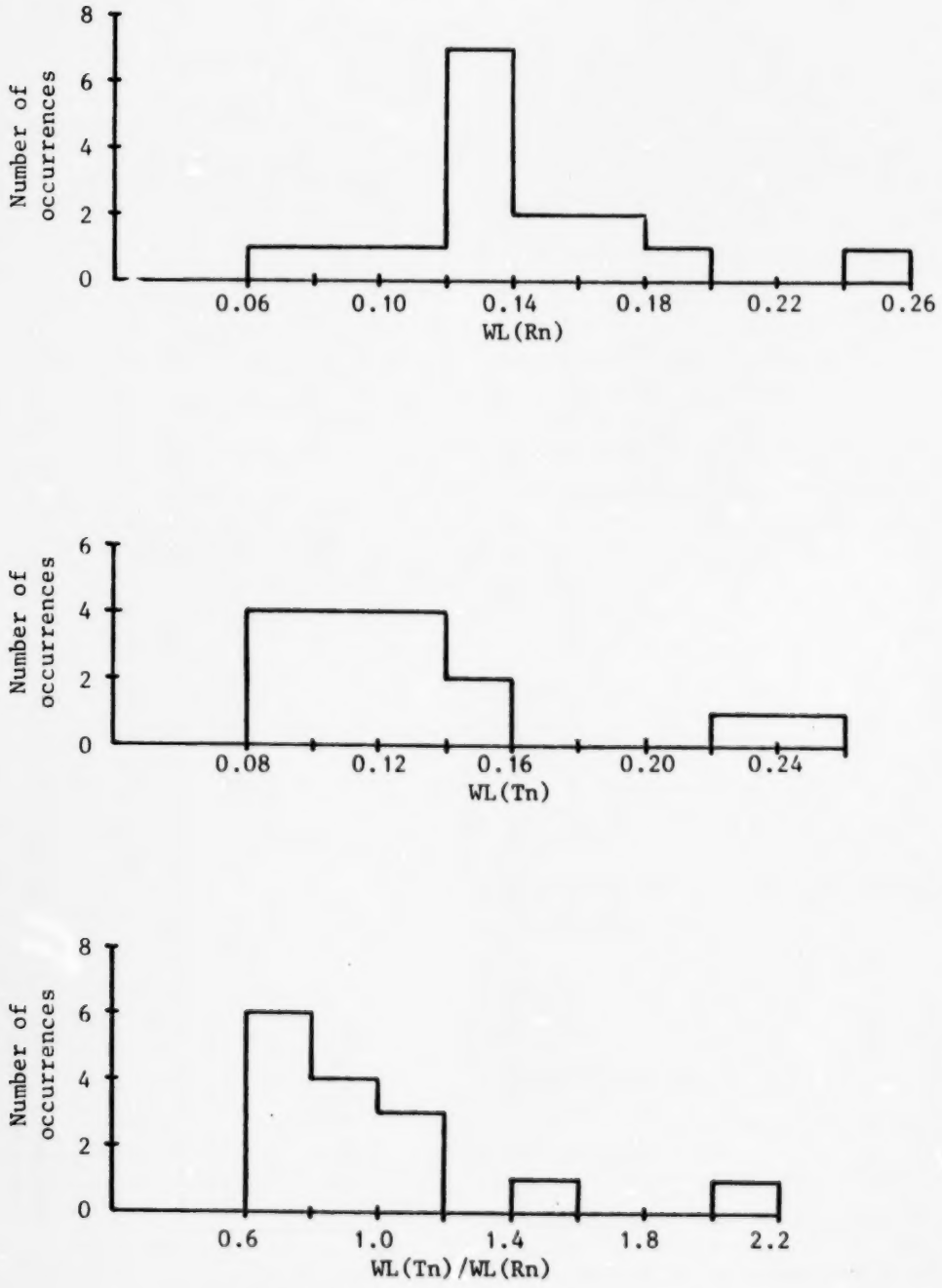



Fig. 30 - Number of occurrences versus WL(Rn), upper curve; WL(Tn), middle curve; and WL(Tn)/WL(Rn), lower curve, for the track-etch dosimeters.

Table 3 - Mean flow-rate and standard deviation of the flow-rate for several dosimeter prototypes (R.A.T.2)

| Dosimeter | Pump No. | Sampling Head No. | $\bar{Q}$, $cm^3/min$ | $\sigma(Q)$ $cm^3/min$ | $\sigma(Q)/\bar{Q} \times 10^2$ |
|---|---|---|---|---|---|
| Track-etch | 205 | 414 | 44.79 | 4.39 | 9.8 |
| " | 206 | 415 | 72.86 | 6.84 | 9.4 |
| " | 208 | 416 | 75.66 | 2.90 | 3.8 |
| " | 209 | 418 | 60.81 | 9.24 | 15.2 |
| " | 210 | 420 | 85.29 | 20.44 | 24.0 |
| " | 211 | 424 | 65.88 | 3.85 | 5.8 |
| " | 213 | 425 | 48.09 | 6.27 | 13.0 |
| " | 212 | 427 | 57.53 | 2.85 | 4.9 |
| " | 214 | 428 | 62.00 | 4.65 | 7.5 |
| " | 215 | 430 | 59.93 | 2.28 | 3.8 |
| " | 216 | 432 | 65.31 | 4.24 | 6.5 |
| " | 217 | 433 | 59.63 | 2.66 | 4.5 |
| " | 223 | 452 | 54.65 | 9.27 | 17.0 |
| " | 224 | 453 | 64.15 | 4.31 | 6.7 |
| " | 225 | 454 | 70.19 | 4.66 | 6.6 |
| " | 218[1] | 450 | - | - | - |
| H & H | 002 | N/A | 18.05 | 4.53 | 25.1 |
| " | 008 | N/A | 123.96 | 27.29 | 22.0 |
| " | 011 | N/A | 128.81 | 34.80 | 27.0 |
| " | 012 | N/A | 147.06 | 6.35 | 4.3 |
| " | 014 | N/A | 173.45 | 15.65 | 9.0 |
| α-NUCLEAR | 004[2] | N/A | 68.25 | - | - |
| " | 008[2] | N/A | 102.45 | - | - |
| " | 012[2] | N/A | 99.17 | - | - |

[1]) Flooded with oil. Only two days of operation.

[2]) Insufficient data to calculate $\sigma(Q)$ and $(\sigma(Q)/\bar{Q})\times 10^2$

Table 4 - Working level data for several dosimeter prototypes (R.A.T.2)

| Date | Dosimeter | WL(Rn) | WL(Tn) | Remarks |
|---|---|---|---|---|
| Feb. 3 | DM003 | 0.19 | 0.13 | PD[1] |
| " | DM008 | 0.17 | 0.13 | SD[2] |
| " | DM012 | 0.28 | 0.18 | PD |
| Feb. 4 | DM004 | 0.16 | 0.04 | PD |
| " | DM008 | 0.09 | 0.08 | SD |
| " | DM012 | 0.16 | 0.11 | PD |
| Feb. 5 | DM008 | 0.33 | 0.32 | SD |
| Feb. 6 | DM004 | 0.09 | 0.01 | PD |
| " | DM008 | 0.13 | 0.11 | SD |
| Feb. 9 | DM004 | 0.27 | 0.06 | PD |
| " | DM008 | 0.41 | 0.35 | SD |
| Feb. 10 | DM004 | 0.22 | 0.05 | PD |
| " | DM008 | 0.53 | 0.50 | SD |
| " | DM012 | 0.26 | 0.21 | PD |
| Feb. 11 | DM008 | 0.03 | 0.03 | SD |
| " | DM012 | 0.29 | 0.23 | PD |
| Feb. 2-20 | H&H001 | - | - | LiF, SD |
| " | H&H002 | 0.123 | 0.2 | LiF, SD |
| " | H&H008 | 0.22 | 0.3 | LiF, SD |
| " | H&H011 | 0.56 | 1.25 | $CaF_2$, SD |
| " | H&H012 | 0.47 | 0.64 | $CaF_2$, SD |
| " | H&H014 | 0.06 | 0.14 | $CaF_2$, SD |
| Feb. 2-20 | α-NUCLEAR | 0.21 | 0.11 | Average of all tests (PD) |

[1]) PD stands for dosimeters used for personal dosimetry.

[2]) SD stands for dosimeters used for site dosimetry.

LiF and $CaF_2$ refer to the TLD material used.

several H & H dosimeters, a different dosimeter each week, were used. Because of this, no direct comparison of the H & H dosimeters with other dosimeter prototypes could be made in this test.

Table 4 shows that the range of values for WL(Rn) and WL(Tn), as determined for the α-NUCLEAR dosimeters and calculated according to the data of Fig. 17 (DM008) and 18 (DM012), agree fairly well with the data obtained from the track-etch dosimeters. (Note: calibration data for DM003 and DM004 were between those for DM008 and DM012.)

Data from the H & H dosimeters using LiF chips (Table 4) indicate that the data are in fair agreement with data from the track-etch dosimeter (Fig. 30) and the α-NUCLEAR dosimeters (Table 4). For $CaF_2$ chips the results are higher and have been obtained by extrapolating the calibration curves of Fig. 19 and 20, considerably beyond their experimental range. The higher than expected readings can be tentatively ascribed to supralinearity of the $CaF_2$ to radiation, a phenomenon that has been previously observed in the calibration of the TLD/CAMPED dosimeter (4).

The average WL(Rn) was 0.21 for the α-NUCLEAR dosimeter and 0.14 for the track-etch dosimeter. The average WL(Tn) was 0.11 for the α-NUCLEAR dosimeter and 0.12 for the track-etch dosimeter. No particular significance should be attached to lack of agreement between the values obtained with the dosimeters as they were worn by different individuals and at different locations.

## R.A.T.3 EXPERIMENTAL RESULTS AND DISCUSSION

The experimental procedure during this test was similar to that corresponding to R.A.T.2. However, no α-NUCLEAR dosimeters were tested for the reasons discussed above.

Figures 31 to 34 show histograms of the track-etch and H & H pump flow-rates versus occurrence or number of events. The data given by these

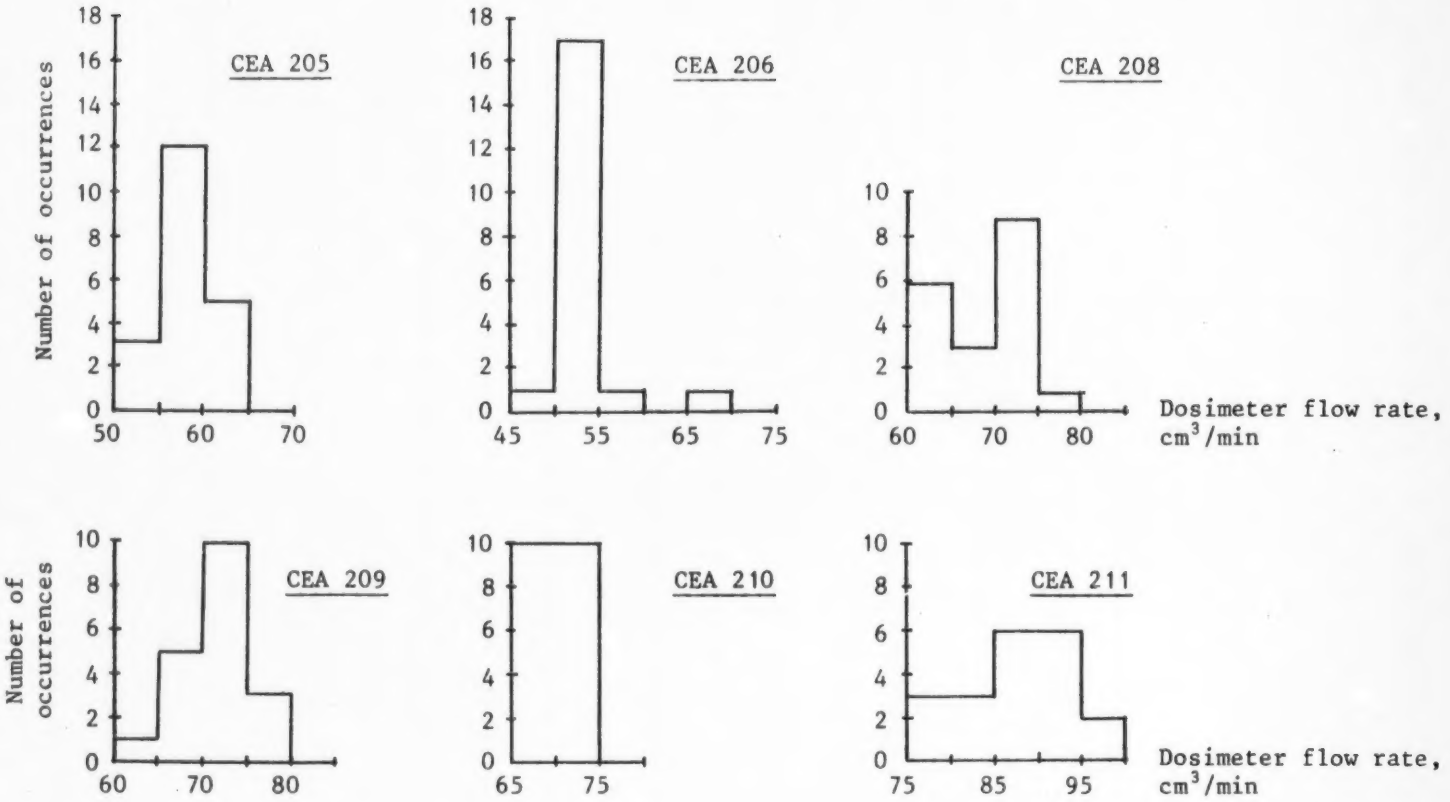



Fig. 31 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 205, 206, 208, 209, 210 and 211.

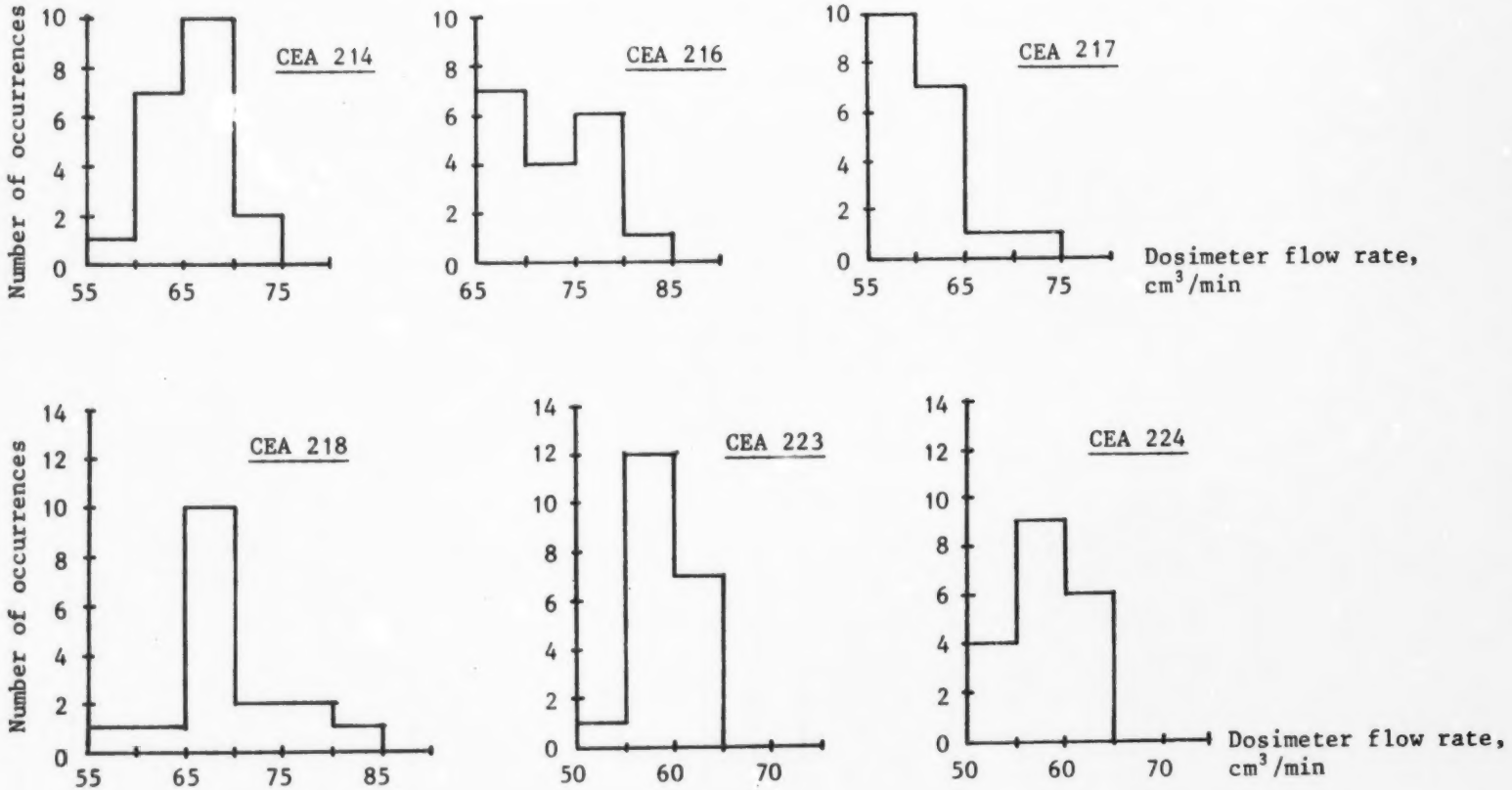



Fig. 32 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 214, 216, 217, 218, 223 and 224.

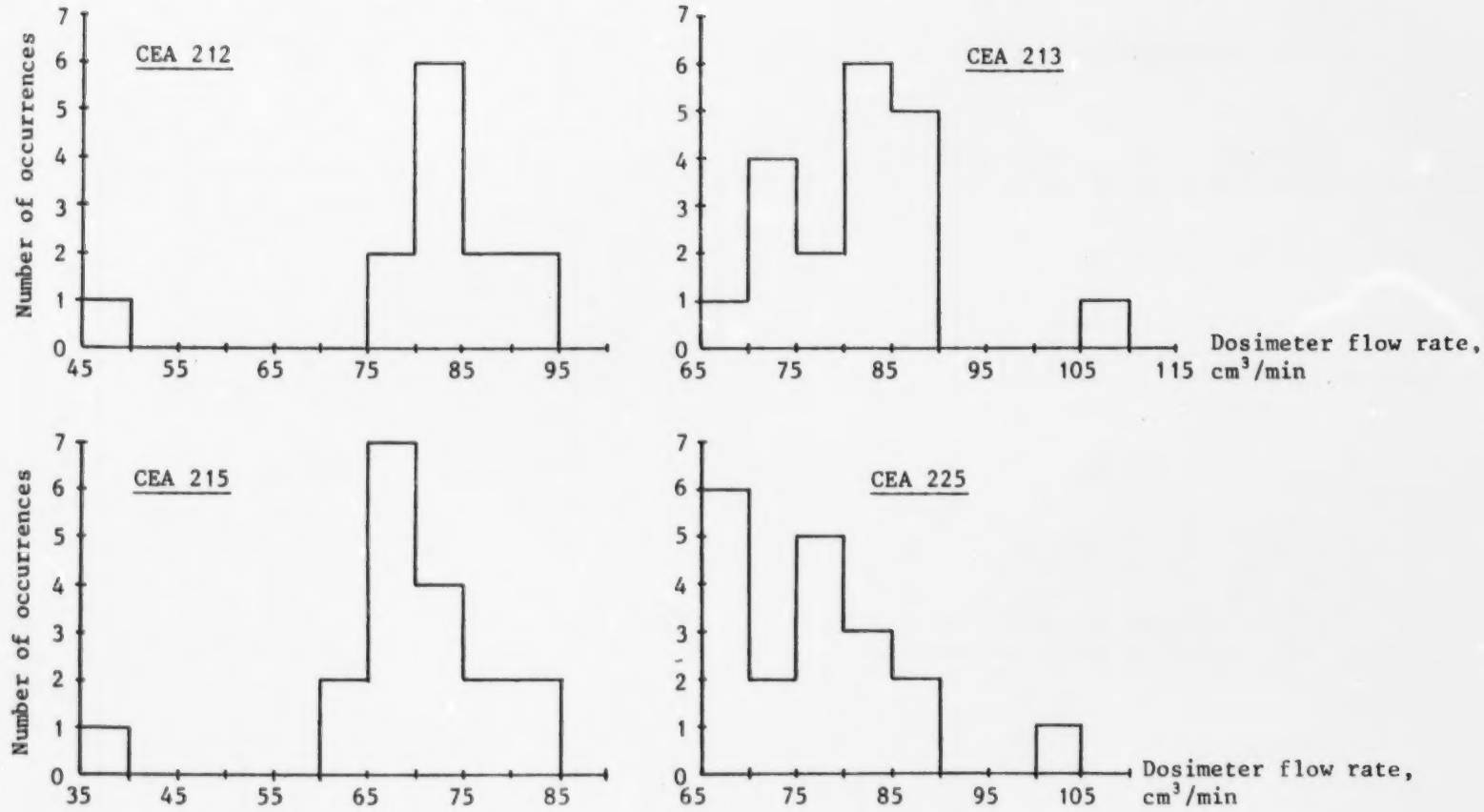



Fig. 33 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 212, 213, 215 and 225.

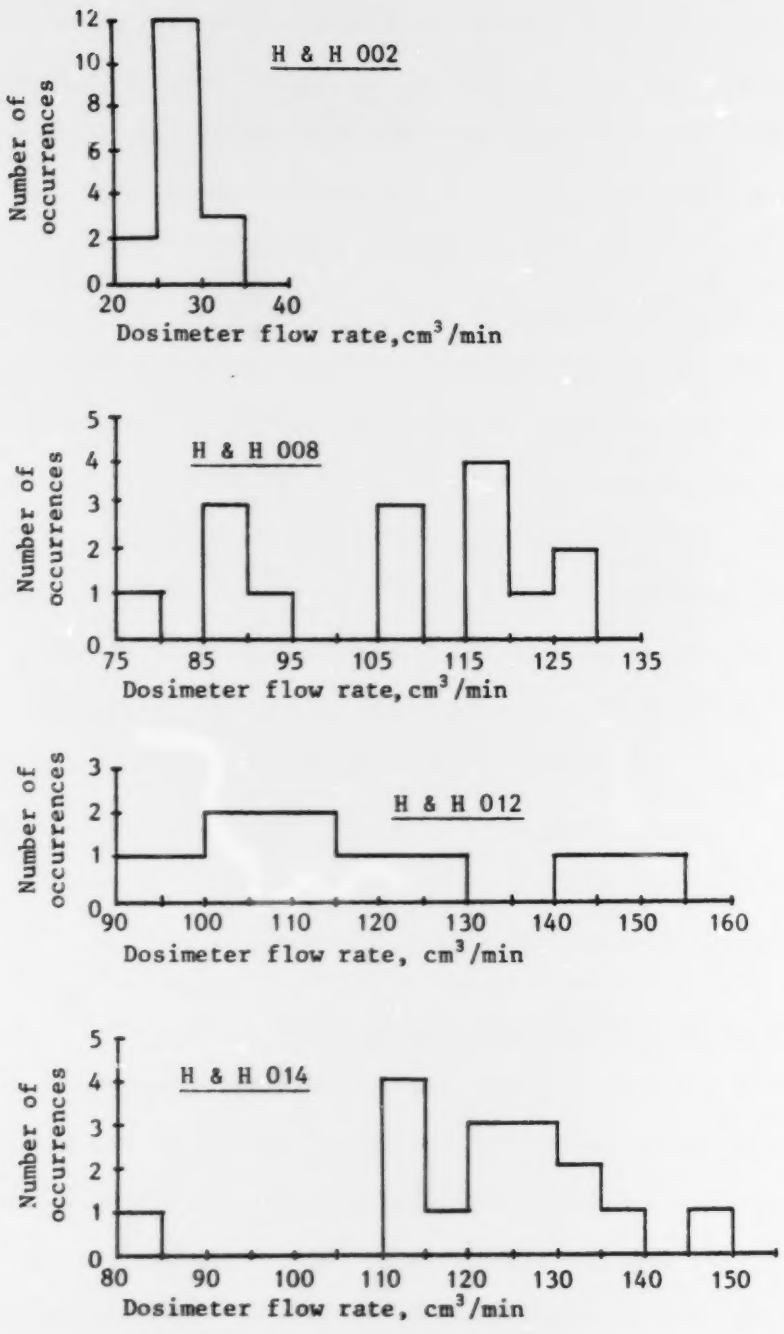



Fig. 34 - Number of occurrences versus dosimeter flow rate for H & H dosimeters H & H 002, 008, 012 and 014.

histograms indicate that, as with the R.A.T.2, flow-rate variations for some track-etch dosimeters were as high as, or higher than, 30%. Flow-rate variations for the H & H dosimeters were even higher than those for the track-etch dosimeters as shown by Fig. 34 and Table 5, which summarizes some flow-rate data pertaining to all the dosimeters tested.

Figure 35 gives, respectively, histograms for WL(Rn), WL(Tn) and the ratio WL(Tn)/WL(Rn), as determined by personal dosimetry using the track-etch detectors. The values obtained for WL(Rn) and WL(Tn) ranged from 0.04 to 0.16 (with an average value of about 0.11) and from 0.06 to 0.12 (with an approximate value of 0.1), respectively. The ratio WL(Tn)/WL(Rn) was bimodal with values mainly between 0.6 to 0.8 and 1.2 to 1.4. These figures agree fairly well with the average value of 0.1 for WL(Rn) determined by three H & H dosimeters (see Table 6) used as personal dosimeters in the same general areas as the track-etch dosimeters. WL(Tn) determined with the H & H dosimeters and Fig. 19 and 20 predict a value of 0.19 (see Table 6), a value almost twice as high as that obtained with the track-etch dosimeters. A possible reason for this discrepancy has been discussed previously.

## R.A.T.4 EXPERIMENTAL RESULTS AND DISCUSSION

The R.A.T.4 was the last underground test carried out at Rio Algom, and only involved the track-etch dosimeters. This test was partly aimed at measuring the thoron daughter contribution deposited in the filter, the long-lived radioactive dust and the effect of filter 'loading' on the α-particle spectrum determined by α-spectroscopy techniques. The studies, not presented here, will be published elsewhere shortly.

Because of the rather short duration of this test, i.e., one-week, not enough data are available for an adequate analysis of flow-rate distribution. Some of the flow-rate data are given in Table 7. This table shows that the

Table 5 - Mean flow-rate ($\overline{Q}$) and standard deviation of the flow-rates ($\sigma(Q)$) for several dosimeter prototypes (R.A.T.3).

| Dosimeter | Pump No. | Sampling Head No. | $\overline{Q}$ ($cm^3/min$) | $\sigma(Q)$ ($cm^3/min$) | $(\sigma(Q)/\overline{Q})\times10^2$ |
|---|---|---|---|---|---|
| Track-etch | 205 | 434 | 58.74 | 2.85 | 4.8 |
| | 206 | 435 | 54.13 | 3.95 | 7.3 |
| | 208 | 436 | 68.08 | 4.49 | 6.5 |
| | 209 | 437 | 72.55 | 3.60 | 5.0 |
| | 210 | 438 | 70.84 | 1.96 | 2.8 |
| | 211 | 439 | 88.05 | 6.16 | 7.0 |
| | 212 | 440 | 81.87 | 11.27 | 13.8 |
| | 213 | 441 | 81.60 | 8.62 | 10.6 |
| | 214 | 442 | 66.02 | 3.66 | 5.5 |
| | 215 | 443 | 70.9 | 9.4 | 13.3 |
| | 216 | 444 | 73.28 | 5.2 | 7.1 |
| | 217 | 445 | 61.85 | 5.12 | 8.3 |
| | 218 | 446 | 69.70 | 5.62 | 8.1 |
| | 223 | 447 | 59.74 | 2.50 | 4.2 |
| | 224 | 448 | 58.15 | 3.37 | 5.8 |
| | 225 | 449 | 77.29 | 8.85 | 11.4 |
| H & H | 002 | N/A | 28.09 | 2.66 | 9.5 |
| | 008 | N/A | 107.86 | 16.84 | 15.6 |
| | 012 | N/A | 118.06 | 19.15 | 16.2 |
| | 014 | N/A | 123.17 | 14.05 | 11.4 |

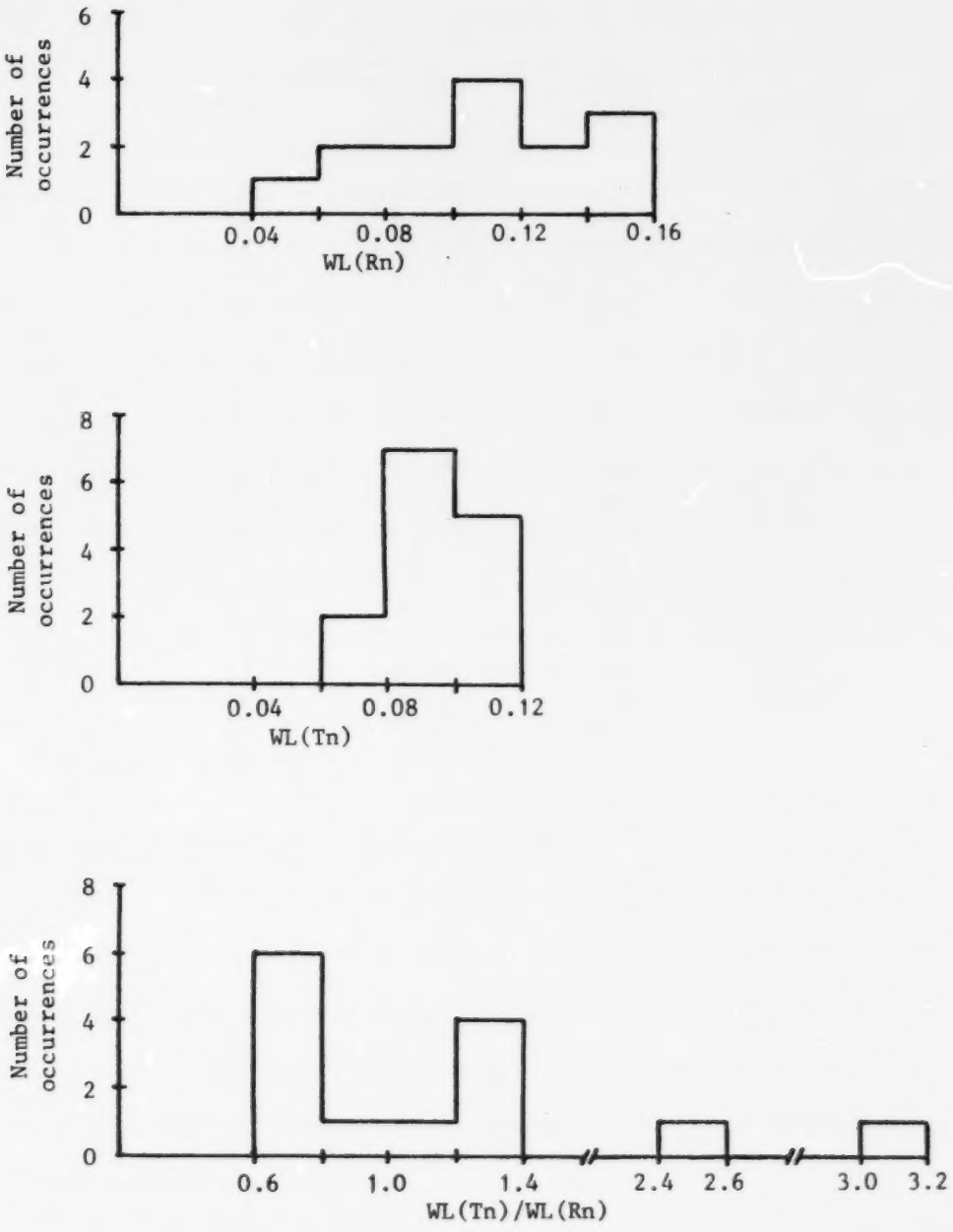



Fig. 35 - Number of occurrences versus WL(Rn), upper graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), lower graph, for track-etch dosimeters.

Table 6 - Working level data for the H & H dosimeters (R.A.T.3).

| Dosimeter | Net Reading nC | Remarks | Air Volume Sampled ($V=\bar{Q}T_s$), L | WL(Rn) | WL(Tn) | $WL_T$ |
|---|---|---|---|---|---|---|
| H & H 002 | 3.60 | LiF, SD | 250.89 | 0.450 | 0.61 | 1.06 |
| H & H 012 | 3.65 | LiF, PD | 896.65 | 0.130 | 0.17 | 0.30 |
| H & H 008 | 17.32 | $CaF_2$, PD | 865.48 | 0.070 | 0.15 | 0.22 |
| H & H 014 | 36.78 | $CaF_2$, PD | 1071.63 | 0.118 | 0.26 | 0.38 |

Remarks: Average WL(Rn) and WL(Tn) for PD dosimeters are 0.11 and 0.19, respectively.

Table 7 - Mean flow-rate ($\bar{Q}$) and standard deviation of the flow-rate ($\sigma(Q)$) for the track etch dosimeters (R.A.T.4).

| Pump No. | Sampling Head No. | $\bar{Q}$ ($cm^3$/min) | $\sigma(Q)$ ($cm^3$/min) | $(\sigma(Q)/\bar{Q})x10^2$ |
|---|---|---|---|---|
| 205 | 414 | 71.80 | 4.23 | 5.9 |
| 206 | 415 | 75.10 | 3.43 | 4.6 |
| 208 | 416 | 71.10 | 3.47 | 4.9 |
| 210 | 420 | 80.74 | 3.28 | 4.1 |
| 211 | 424 | 88.93 | 2.32 | 2.6 |
| 212 | 425 | 87.80 | 4.78 | 5.4 |
| 213 | 427 | 82.84 | 3.23 | 3.9 |
| 214 | 429 | 89.34 | 11.14 | 12.5 |
| 215 | 430 | 82.76 | 3.61 | 4.4 |
| 216 | 432 | 73.66 | 3.32 | 4.5 |
| 217 | 433 | 76.22 | 5.16 | 6.8 |
| 218 | 450 | 83.08 | 1.97 | 2.4 |
| 223 | 452 | 67.46 | 1.71 | 2.5 |
| 224 | 453 | 77.75 | 6.12 | 7.9 |
| 225 | 454 | 76.33 | 2.71 | 3.5 |

spread of flow-rate values, as measured by the ratio $(\sigma(Q)/\bar{Q})\times 10^2$, is somewhat less than that corresponding to the other longer duration tests (see Tables 3 and 5). This seemingly improved pump performance can tentatively be attributed to reduced filter loading that puts less strain on the pump.

Figure 36 shows histograms of WL(Rn), WL(Tn) and the ratio WL(Tn)/WL(Rn), respectively. As with previous underground personal dosimetry tests, Fig. 36 shows a wide range of values for the above variables: from 0.02 to 0.28 with an average value of approximately 0.11 for WL(Rn); from 0.02 to 0.2 with an average value close to 0.1 for WL(Tn); and from 0.4 to 1.6 with a maximum occurrence in the range from 0.6 to 0.8 for the ratio WL(Tn)/WL(Rn). These values are in fair agreement with values determined in R.A.T.2 and R.A.T.3.

## RESULTS AND DISCUSSION OF LONG-TERM CALIBRATION TESTS R.A.T.2, R.A.T.3 & R.A.T.4

The WL(Rn) profile for the three site dosimetry tests conducted at the exhaust of Shaft No. 1 is shown in Fig. 37. Each data point represents the mean value of two daily WL(Rn) measurements, one early in the morning and one late in the afternoon. Data pertaining to some dosimeters are also shown in the graph.

Figure 37 shows large fluctuations in the mean value of the WL(Rn) as determined by grab-sampling. Daily WL(Rn) measurements seemed to be more constant in the afternoon than in the morning (data not shown). The WL(Rn) as determined by several dosimeters is also indicated in Fig. 37. This figure shows that in most cases the WL(Rn) determined by grab-sampling is significantly lower than that determined by the dosimeters. We also notice that no data for the H & H dosimeters are available during R.A.T.2 because, as indicated above, different dosimeters were mistakenly used during the test. The same also applies regarding the track-etch dosimeters during R.A.T.3. Only limited data are available for the α-NUCLEAR dosimeter during R.A.T.2 for reasons indicated

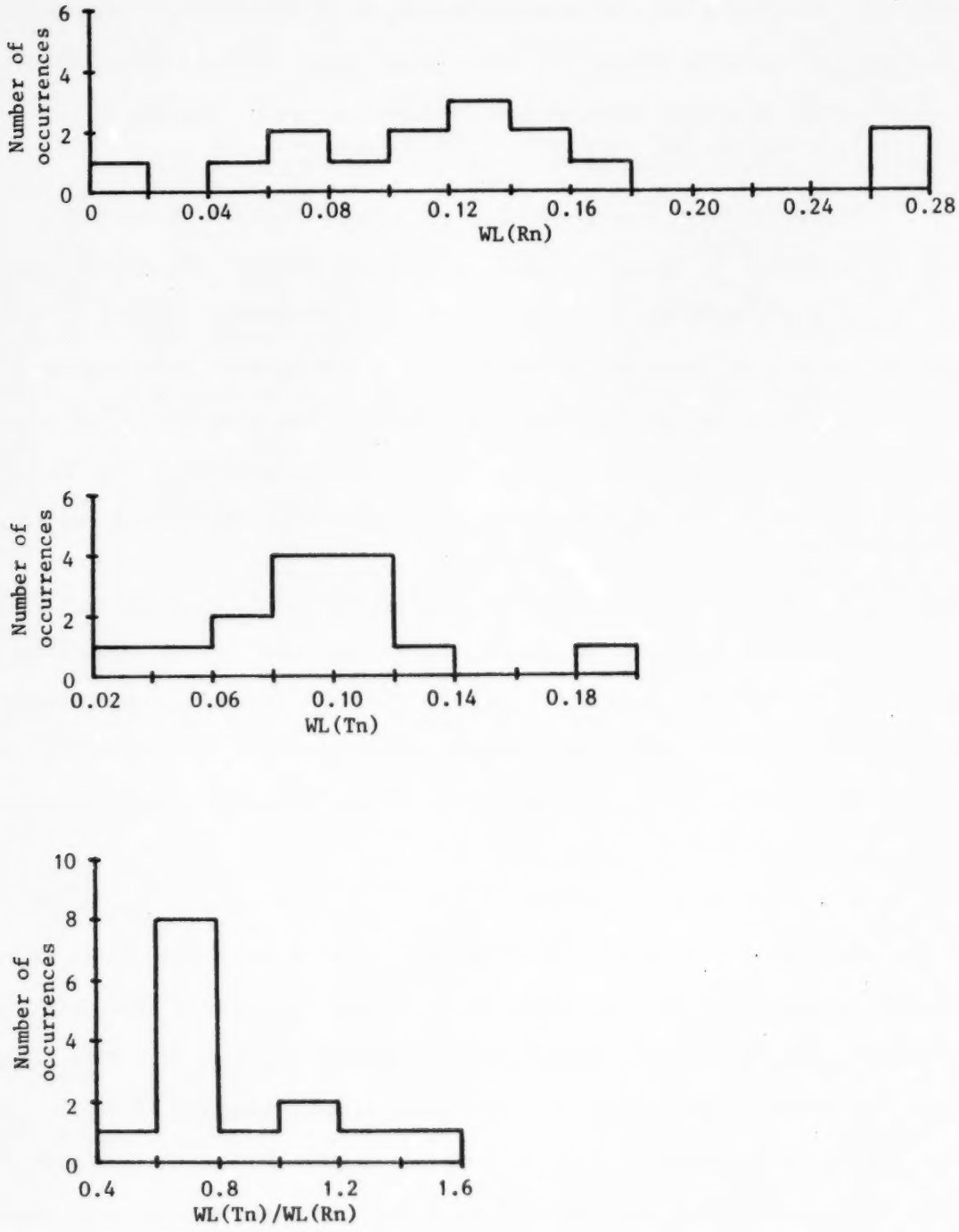



Fig. 36 - Number of occurrences versus WL(Rn), upper graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), lower graph, for track-etch dosimeters.

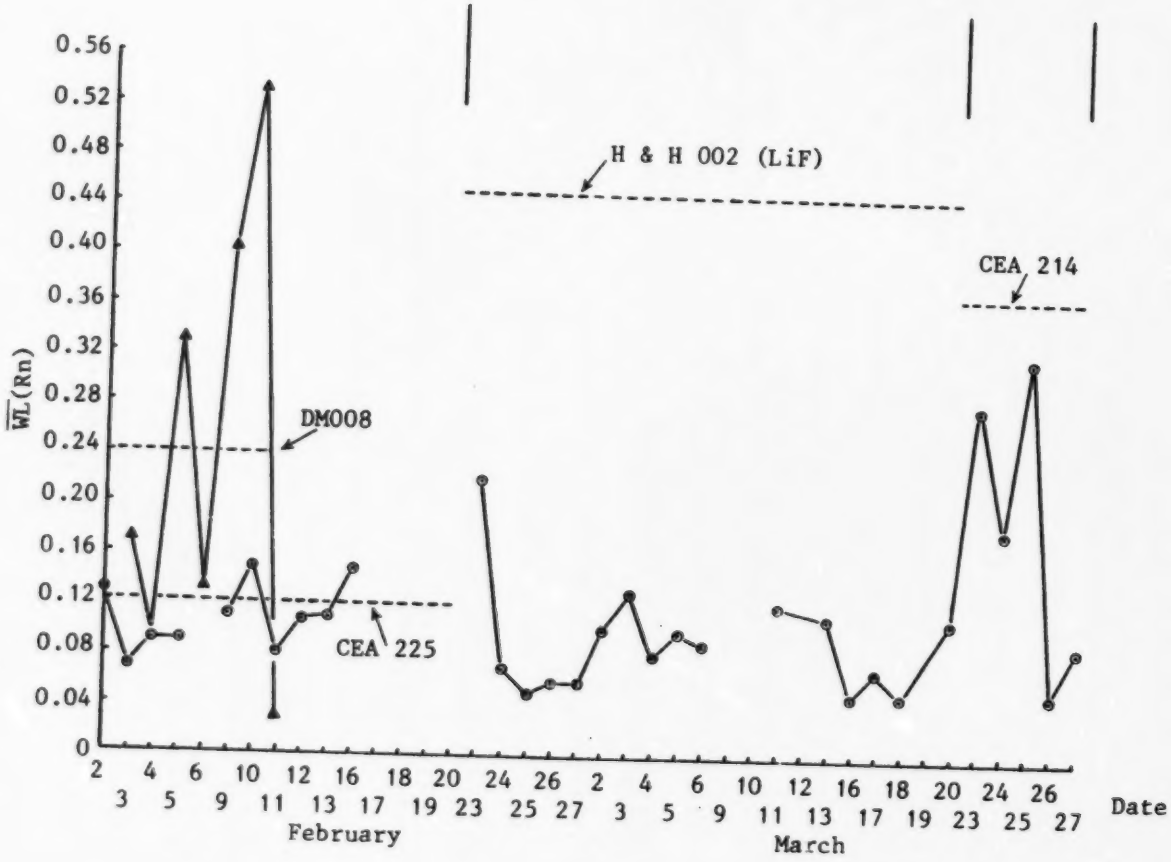



Fig. 37 - Daily average WL, i.e., $\overline{WL}$(Rn), by grab-sampling versus date. Also shown in the figure are the average WL(Rn) determined by several dosimeters (broken lines). The length of the broken lines indicate the length of time over which the average was determined. Daily grab-sampling data points shown represent the mean value of two daily measurements.

above. No data other than that corresponding to the track-etch dosimeter are available for R.A.T.4, as the α-NUCLEAR and H & H dosimeters were not used in this test.

Although the WL(Rn) data obtained for the dosimeters and by grab-sampling are significant when considered separately, no firm conclusion can be arrived at when comparing those data as grab-sampling measurements were, unfortunately, not done at the same location where the dosimeters were located. It was observed that while the dosimeters had been placed about 2 m deep from the exit of the exhaust shaft, grab-sampling measurements were taken at the 'exit' of the shaft, where radiation levels presumably would be lower. This might, in principle and partly, explain the discrepancy observed. Another potential source of error in sampling procedures was identified, namely, the site dosimetry dosimeters were all tied together and lowered down the shaft where they were left suspended in mid-air with the air stream flowing parallel, instead of perpendicular, to the dosimeters and opposite to the sampling head. Hence, and in all likelihood, the dosimeters were subjected to strong eddies and 'shadow' effects. Furthermore, it is doubtful that sampling was done under isokinetic conditions for either the dosimeters or grab-samplers. (Note: the dosimeters operated at a flow-rate of about 0.1 L/min. Grab-sampling was done at flow-rates of about 6 L/min.) Finally, the α-NUCLEAR readings are not fully reliable because of the dosimeter's power pack problems encountered in these earlier tests. Because of the experimental difficulties indicated above, the results of the site dosimetry test shown in Fig. 37 should be regarded as inconclusive.

## UNDERGROUND TESTS AT DENISON MINES

Four underground tests were conducted at Denison Mines Ltd., namely: two long-term personal dosimetry tests of four-weeks duration each, one site dosimetry test of one-week duration, and a short-term personal dosimetry test. (As the Denison Mine at Elliot Lake is trackless, the dosimeters were fully tested under diesel conditions.) A reduced number of dosimeters were used as site dosimeters in the personal dosimetry tests (i.e., for long-term calibration purposes). The site dosimeters were placed in an area where environmental conditions, including radiation level, remained as constant as reasonably possible. The long-term personal dosimetry tests were conducted in areas where ore was being mined. The short-term personal dosimetry test was carried out in an area of the mine where ore leaching was done. The site dosimetry test was conducted near a crusher, which operated regularly during the normal working shift. As at Rio Algom, environmental conditions at Denison Mines varied substantially from day to day and from location to location. Figure 38 shows air-flow data for several locations where the tests were carried out.

Personnel at the Ventilation Department of Denison Mines were responsible for assigning and delivering the dosimeters to underground workers (or the crew captain) and for picking up the dosimeters when the workers returned to the surface at the end of the shift. They were also responsible for conducting daily flow-rate measurements, reading the α-NUCLEAR dosimeters and changing the α-NUCLEAR filters daily. Furthermore, an environmental technician was assigned by Denison Mines to conduct radiation and meteorological data measurements at the personal and site dosimetry areas. He was also in close contact with the underground crew, thereby ensuring that practical daily problems arising underground could be promptly solved, whenever possible,

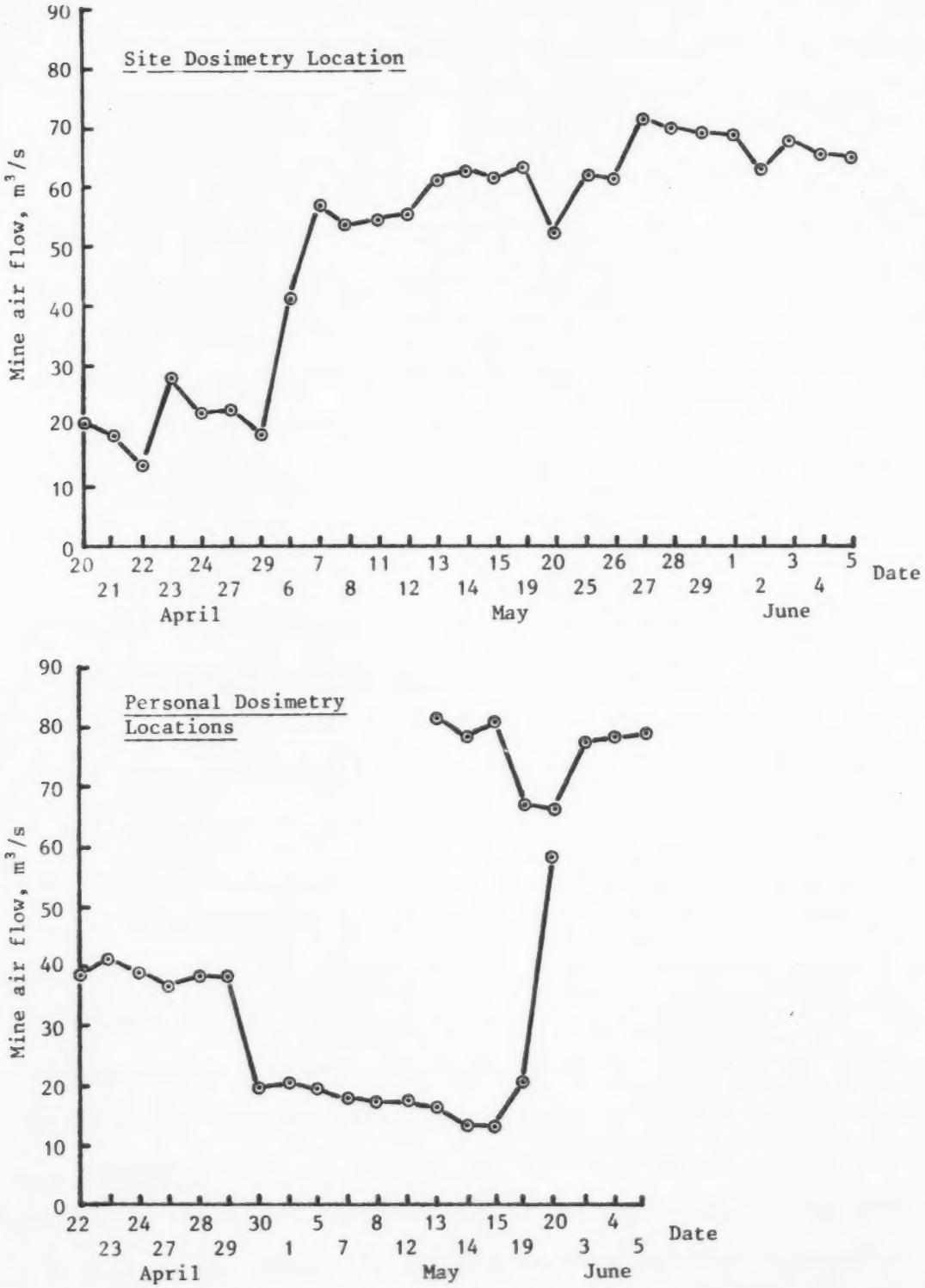



Fig. 38 - Mine air flow versus date for several underground experimental locations: side dosimetry, upper graph; and personal dosimetry, lower graphs.

with a minimum of disturbance to the program. This working arrangement helped a great deal in bringing the tests to a successful completion. The technician wore a dosimeter of each kind to procure 'accurate' personal dosimetry data. The changing of filters, and processing and reading of the other dosimeters, as well as the analysis of all data collected during the tests was the responsibility of CANMET staff.

Because of wear and tear in previous underground tests at Rio Algom, several dosimeters (2 H & H dosimeters and 1 track-etch dosimeter) were eliminated from further underground testing. Thus, the total number of dosimeters used was as follows: 15 track-etch, 4 H & H and 4 α-NUCLEAR.

## D.M.T.1 PERSONAL DOSIMETRY AND LONG-TERM CALIBRATION TESTS: RESULTS AND DISCUSSION

Figures 39 to 44 show histograms of the flow-rate for each of the track-etch, H & H and α-NUCLEAR dosimeters used. Individual flow-rate variations were on the average about 30%, except for the H & H dosimeters which exhibited consistently larger variations. Table 8 gives the average flow-rate, $\overline{Q}$, standard deviation of $\overline{Q}$, and the performance index $(\sigma(Q)/\overline{Q})\times10^2$ for the track-etch dosimeters over the H & H dosimeters.

Figures 45 and 46 show histograms of WL(Rn), WL(Tn) and the ratio WL(Tn)/WL(Rn) as determined by the track-etch and α-NUCLEAR dosimeters, respectively. Figure 45 also shows a histogram of WL(Rn) from grab-sampling data taken during the underground test in the areas where the personal dosimetry program was conducted. A comparison of the WL(Rn) histograms for the track-etch, α-NUCLEAR dosimeters and the grab-sampling data indicates a wider spread for the latter with a maximum at lower levels. Most WL(Rn) readings for the track-etch and α-NUCLEAR dosimeters were in the range 0.06 to 0.11, whereas most of the WL(Rn) determined by grab-sampling had values in the range 0.02

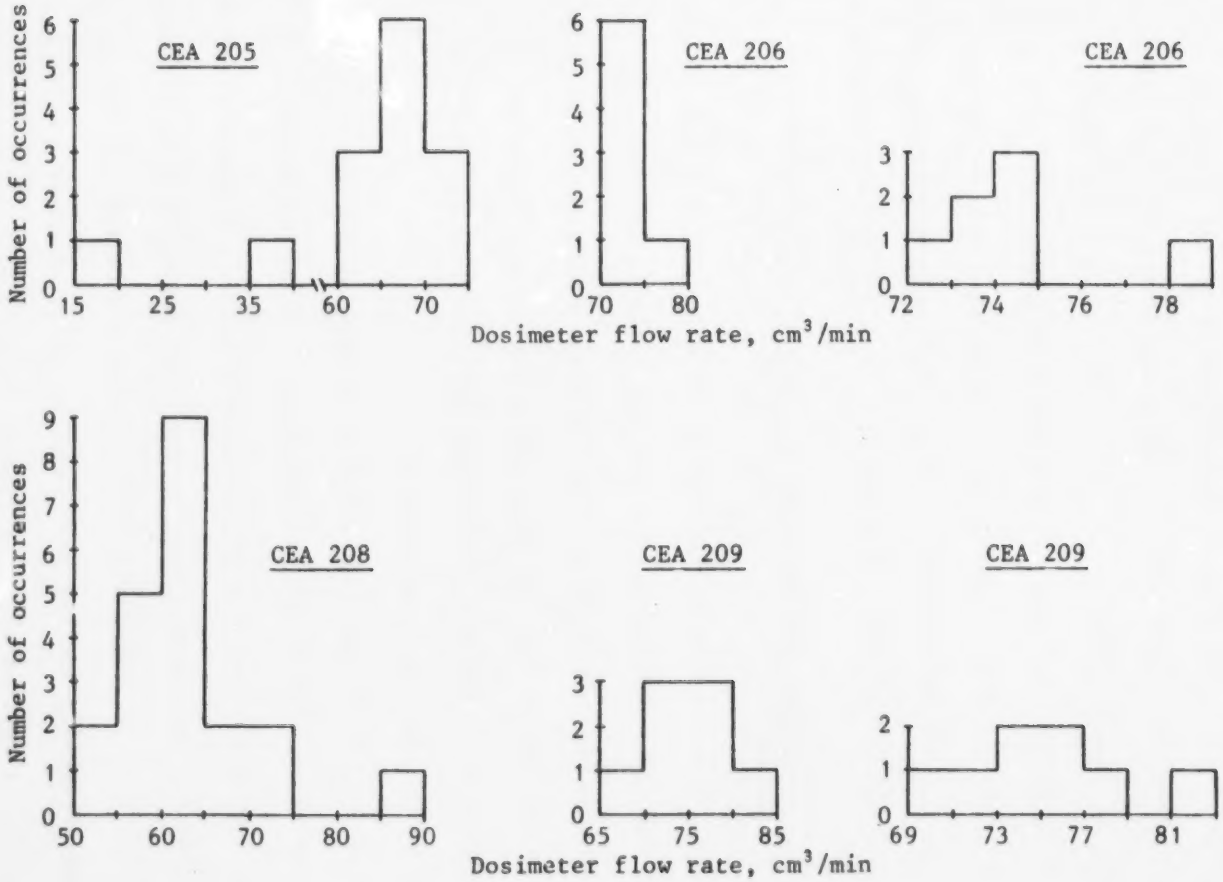



Fig. 39 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 205, 206, 208 and 209.

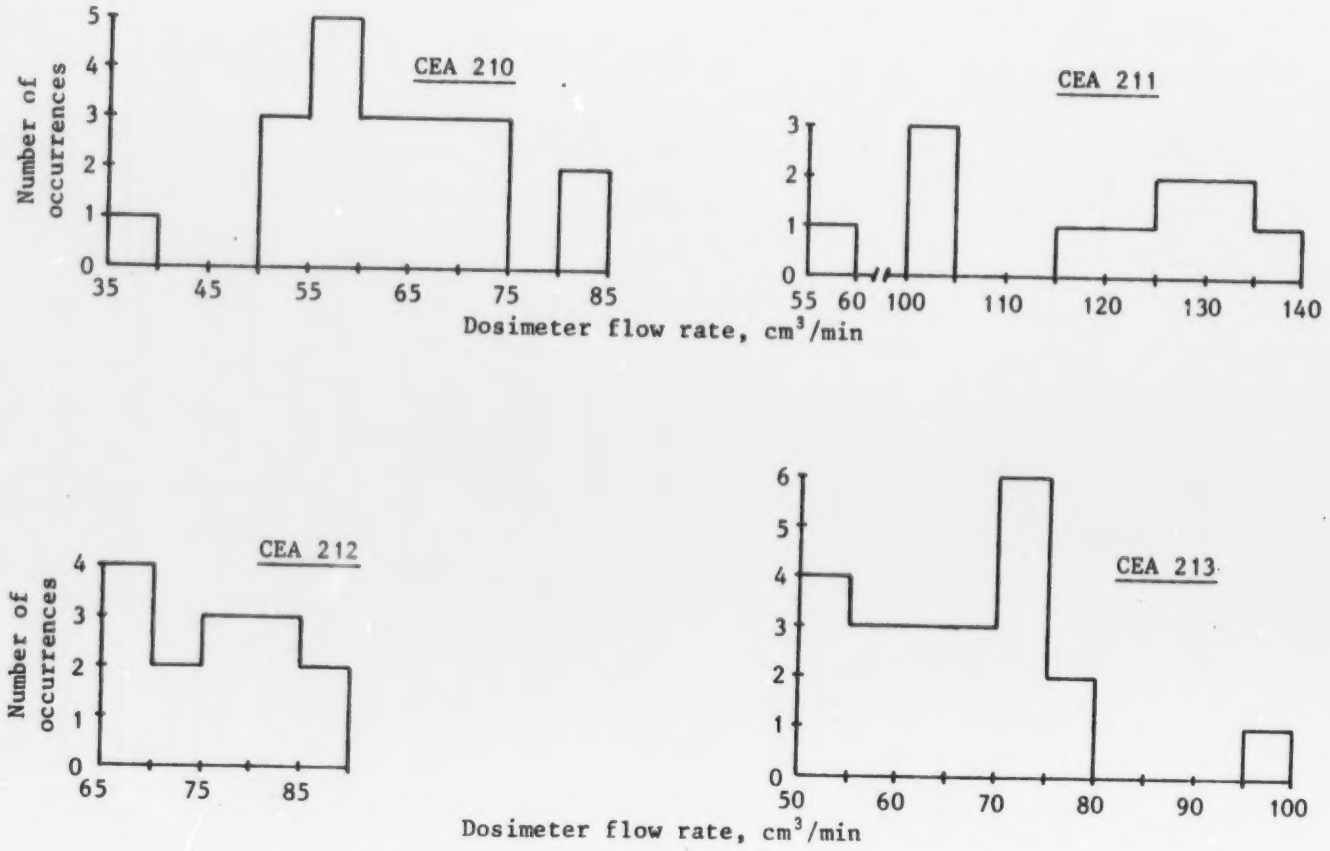



Fig. 40 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 210, 211, 212 and 213.

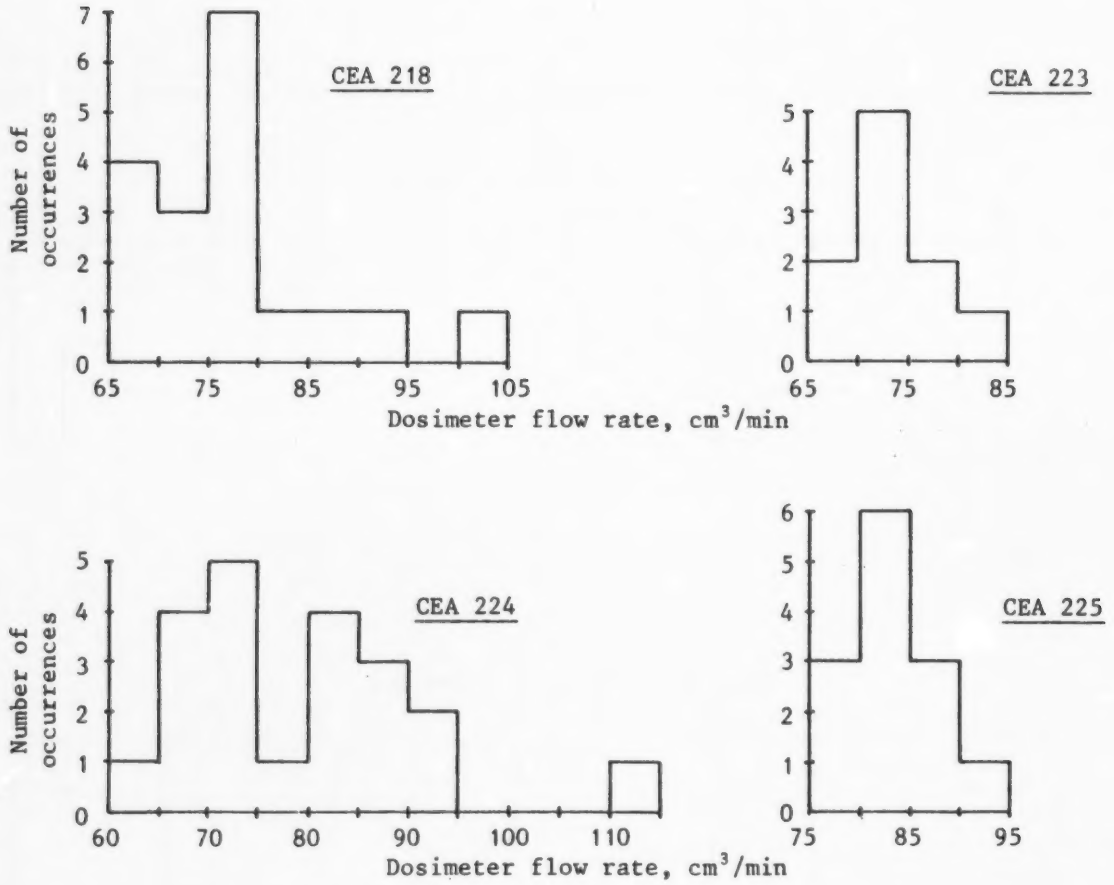



Fig. 41 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 218, 223, 224 and 225.

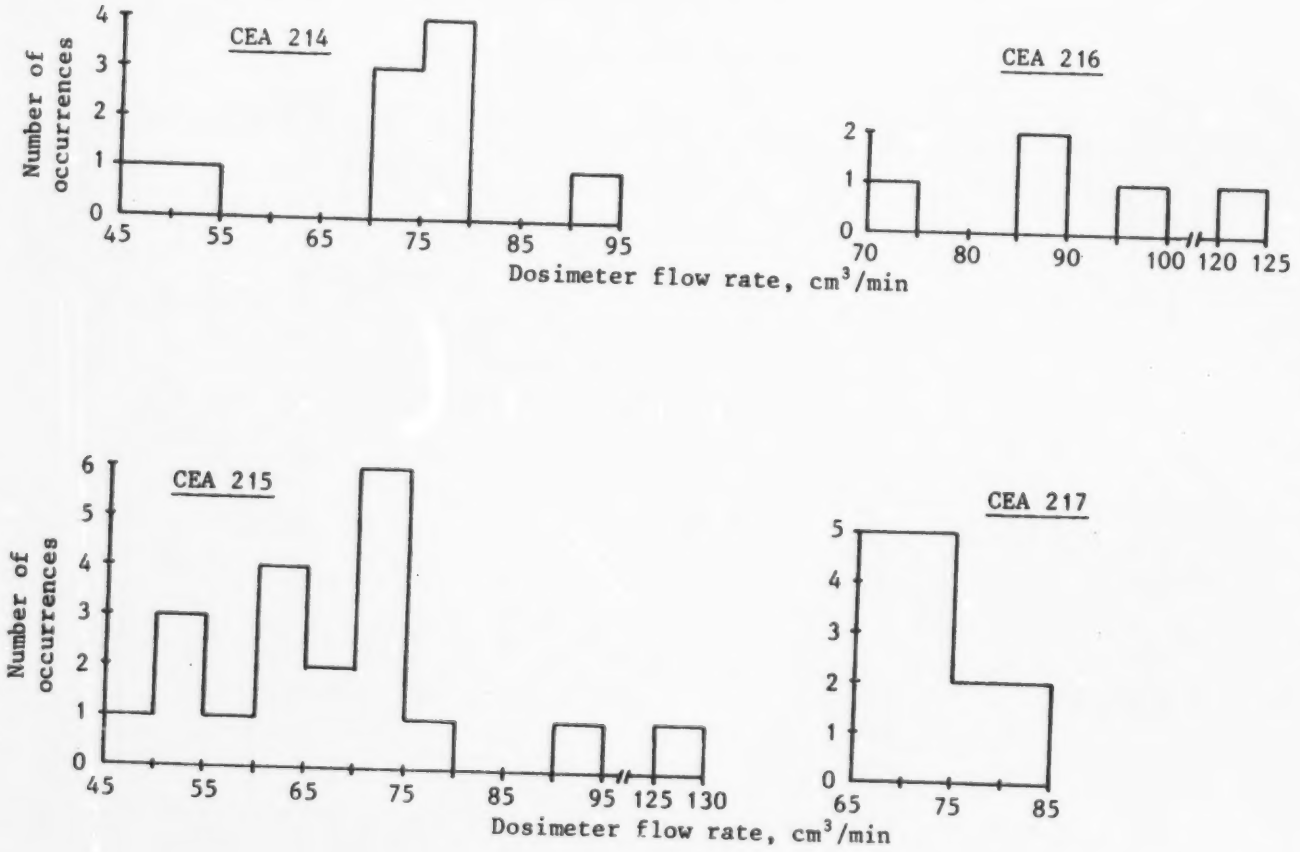



Fig. 42 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 214, 216, 215 and 217.

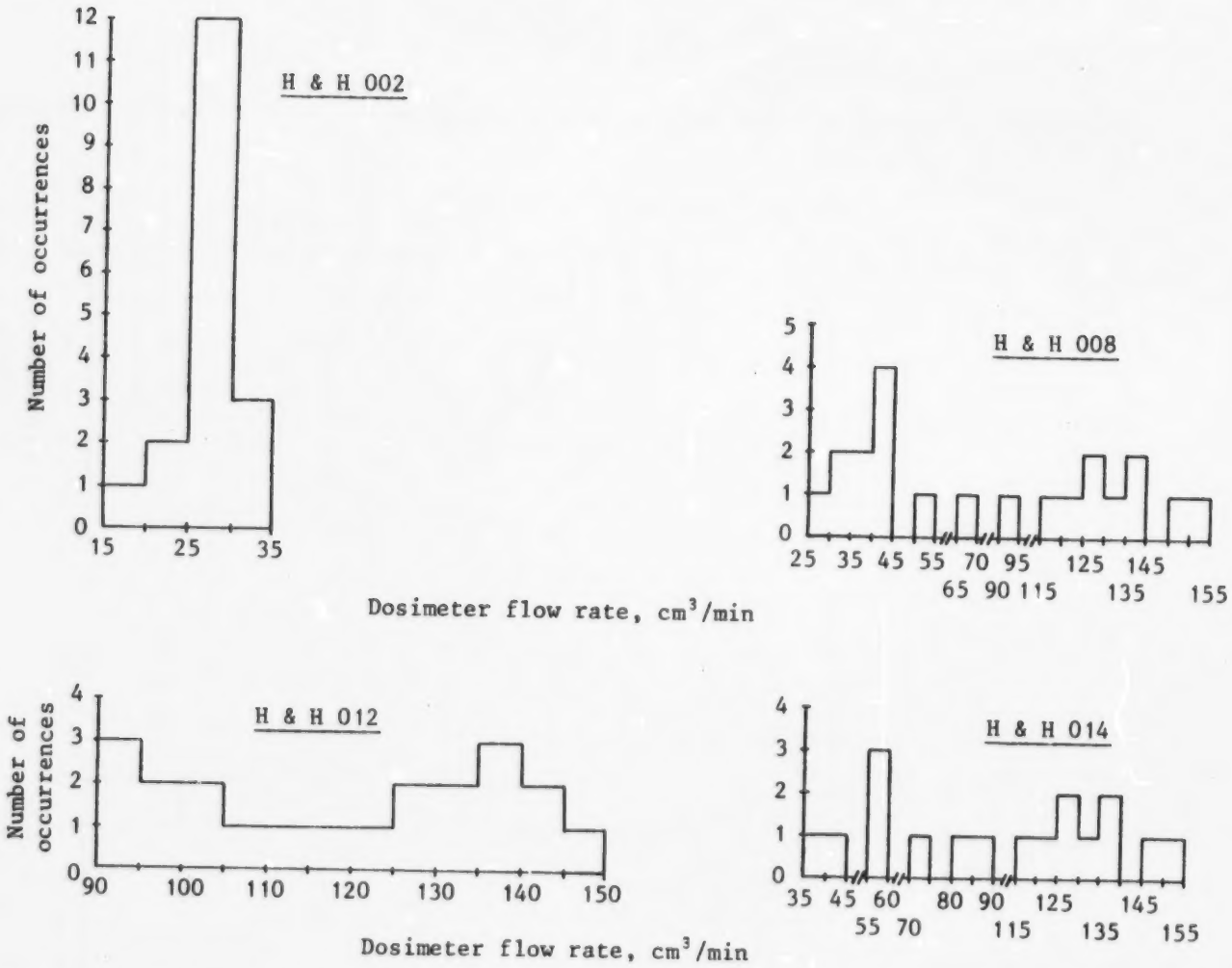



Fig. 43 - Number of occurrences versus dosimeter flow rate for H & H dosimeters H & H 002, 008, 012 and 014.

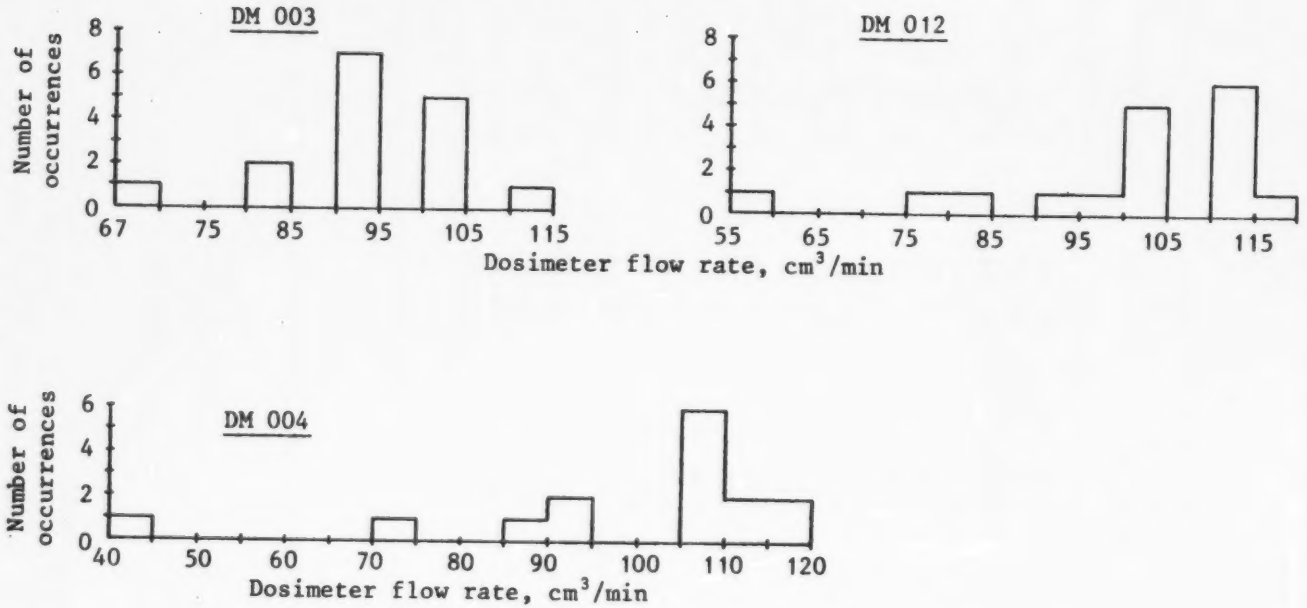



Fig. 44 - Number of occurrences versus dosimeter flow rate for α-NUCLEAR dosimeters DM 003, 012 and 004.

Table 8 - Mean flow-rate and standard deviation of the flow-rate for several dosimeter prototypes (D.M.T.1).

| Dosimeter | Pump No. | Sampling Head No. | $\bar{Q}$ ($cm^3$/min) | $\sigma(Q)$ ($cm^3$/min) | $(\sigma(Q)/\bar{Q}) \times 10^2$ |
|---|---|---|---|---|---|
| Track-etch | 205 | 434 | 67.57 | 3.91 | 5.8 |
| | 206 | 435 | 74.67 | 2.18 | 2.9 |
| | 208 | 436 | 63.28 | 7.86 | 12.4 |
| | 209 | 437 | 75.45 | 3.79 | 5.0 |
| | 210 | 438 | 63.83 | 9.03 | 14.1 |
| | 211 | 439 | 119.20 | 13.84 | 11.6 |
| | 212 | 441 | 75.95 | 7.44 | 9.8 |
| | 213 | 440 | 65.46 | 10.74 | 16.4 |
| | 214 | 442 | 81.69 | 12.43 | 15.2 |
| | 215 | 443 | 69.15 | 17.34 | 25.1 |
| | 216 | 444 | 92.36 | 18.88 | 20.4 |
| | 217 | 445 | 72.63 | 5.22 | 7.2 |
| | 218 | 446 | 77.56 | 9.53 | 12.3 |
| | 223 | 447 | 73.28 | 4.79 | 6.5 |
| | 224 | 448 | 79.30 | 11.62 | 14.6 |
| | 225 | 449 | 82.46 | 4.18 | 5.1 |
| H & H | 002 | N/A | 26.82 | 3.47 | 12.9 |
| | 008 | N/A | 83.03 | 46.88* | 56.5 |
| | 012 | N/A | 84.78 | 34.01* | 40.1 |
| | 014 | N/A | 118.74 | 10.90 | 9.2 |

* Considerable deterioration of pump performance or filter loading or both.

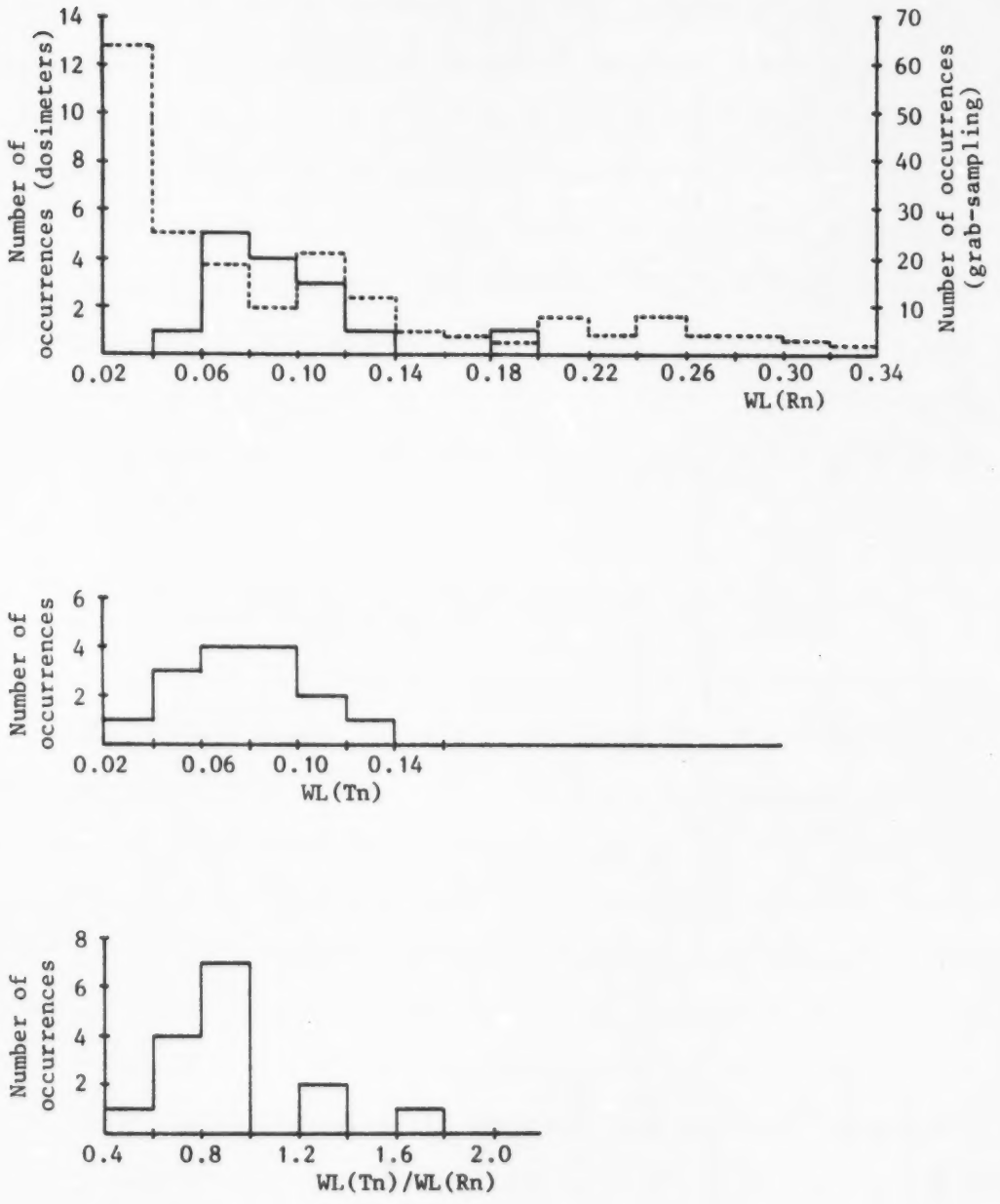



Fig. 45 - Number of occurrences versus WL(Rn), upper graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), lower graph, for track-etch dosimeters. Broken lines in upper graph show the number of occurrences versus WL(Rn) by grab-sampling.

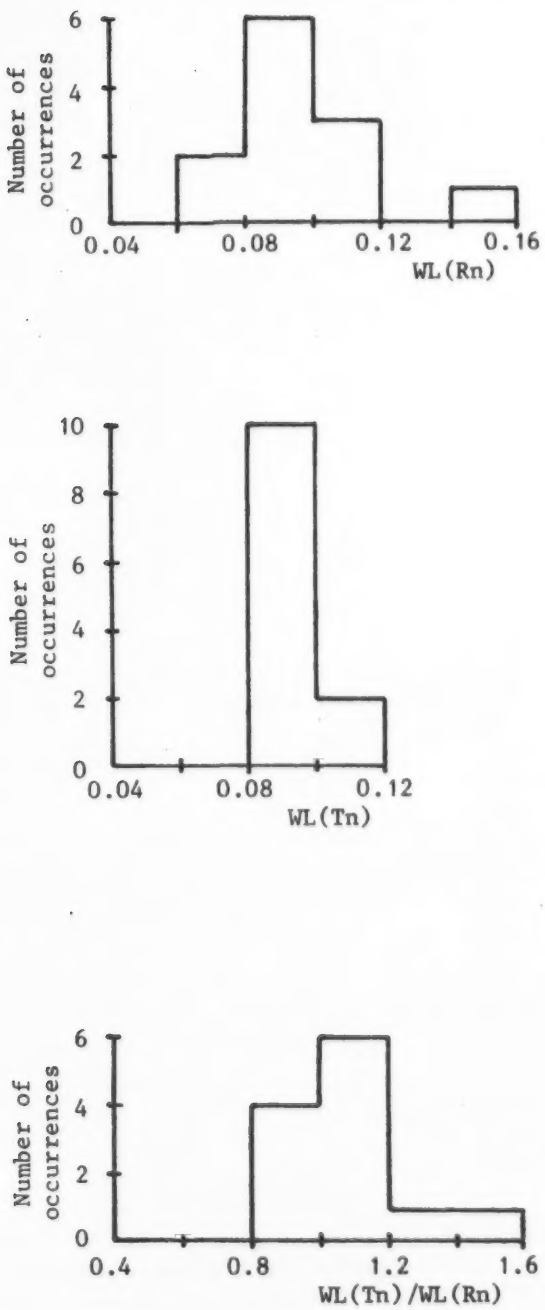



Fig. 46 - Number of occurrences versus WL(Rn), upper graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), lower graph, for α-NUCLEAR dosimeters.

to 0.12. A comparison of Fig. 45 and 46 shows a wider spread of values of WL(Tn) for the track-etch dosimeters than with α-NUCLEAR dosimeters. The maximum of the distributions is in fair agreement, however, with a value in the range of 0.07 to 0.10. In general, the ratio WL(Tn)/WL(Rn) was found to be slightly higher for the α-NUCLEAR than for the track-etch dosimeters.

The above data indicate that except for the WL(Rn) measured with the H & H dosimeters, the data determined with the three types of dosimeters used are in fair to good agreement (i.e., within 10-30%) with one another, and with grab-sampling data (see Table 9). A comparison of grab-sampling data and site dosimetry data corresponding to D.M.T.1 and D.M.T.2 is discussed at the end of D.M.T.2.

## D.M.T.2 PERSONAL DOSIMETRY AND LONG-TERM CALIBRATION TESTS: EXPERIMENTAL RESULTS AND DISCUSSION

Figures 47 to 52 show histograms of the flow-rate for the track-etch, H & H and α-NUCLEAR dosimeters used. Individual flow rate variations were on the average about 30%, or more, except for the H & H dosimeters which exhibited consistently larger variations. Table 10 gives $\overline{Q}$, $\sigma(Q)$ and $(\sigma(Q)/\overline{Q}) \times 10^2$ dosimeters tested. This Table shows that in terms of the average of the index $(\sigma(Q)x\overline{Q})x10^2$, α-NUCLEAR dosimeters performed best followed by track-etch dosimeters which in turn performed better than H & H dosimeters.

Figures 53 and 54 show histograms of WL(Rn), WL(Tn) and the ratio WL(Tn)/WL(Rn) as determined by the track-etch and α-NUCLEAR dosimeters. Figure 53 also shows a histogram of WL(Rn) from grab-sampling data obtained in the course of the underground test in the areas where the personal dosimetry program was carried out. A comparison of the WL(Rn) histograms for the track-etch and α-NUCLEAR dosimeters, and the grab-sampling data, indicates a much wider distribution for the latter, with a maximum at slightly lower values of

Table 9 - Working level data for several dosimeter prototypes (D.M.T.1).

| Dosimeter | Remarks | WL(Rn) | $\overline{WL}$(Rn) | | | WL(Tn) | $\overline{WL}$(Tn) | | | $WL_T$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | S.D. | P.D. | Total[1] | | S.D. | P.D. | Total[1] | |
| H & H 002 | LiF, S.D. | 0.040 | | | | 0.080 | | | | 0.120 |
| H & H 008 | $CaF_2$, P.D. | 0.030 | 0.040 | 0.057 | 0.053 | 0.060 | 0.080 | 0.100 | 0.100 | 0.090 |
| H & H 012 | LiF, P.D. | 0.090 | | | | 0.130 | | | | 0.220 |
| H & H 014 | $CaF_2$, P.D. | 0.050 | | | | 0.120 | | | | 0.170 |
| DM 003 | S.D. | 0.108 | | | | 0.108 | | | | 0.216 |
| DM 004 | P.D. | 0.103 | 0.117 | 0.085 | 0.098 | 0.108 | 0.117 | 0.095 | 0.105 | 0.211 |
| DM 008 | S.D. | 0.130 | | | | 0.128 | | | | 0.258 |
| DM 012 | P.D. | 0.082 | | | | 0.091 | | | | 0.173 |
| Track-etch* | | 0.096 | 0.119 | 0.094 | 0.096 | 0.085 | 0.099 | 0.084 | 0.085 | 0.180 |
| Grab-sampling | | 0.110 | | | | | | | | |

* all S.D. dosimeters, or all P.D. dosimeters, or <u>all</u> dosimeters.

[1]) indicates the average value obtained with all dosimeters tested, i.e., P.D. plus S.D.

Note: S.D. and P.D. stand for dosimeters used for site dosimetry and personal dosimetry, respectively.

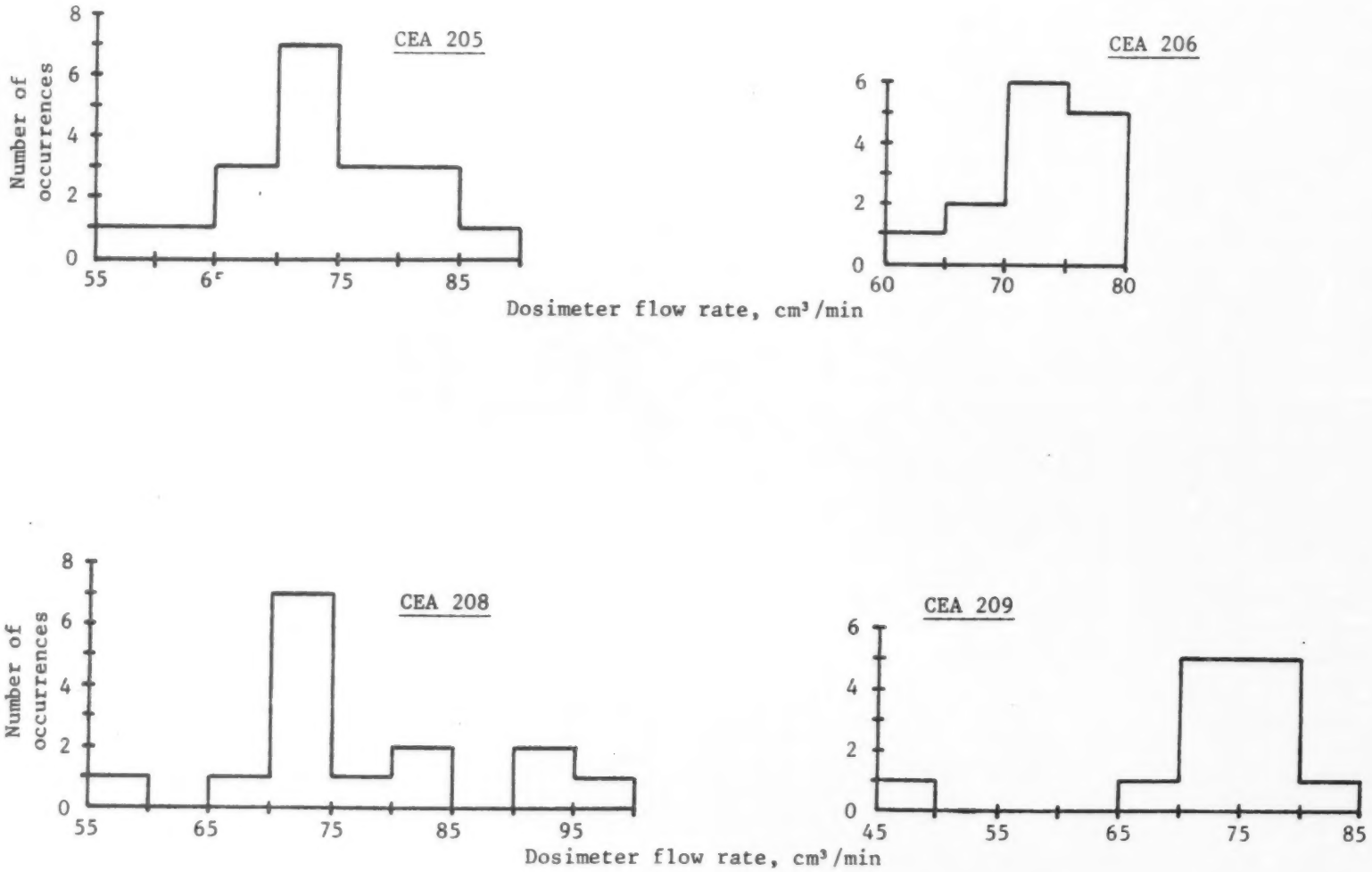
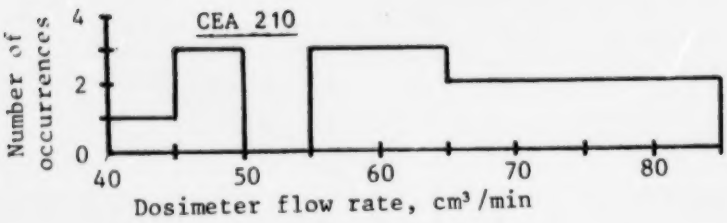
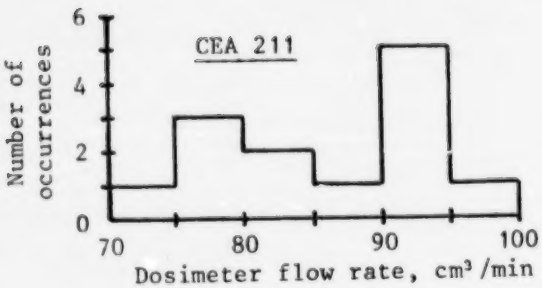
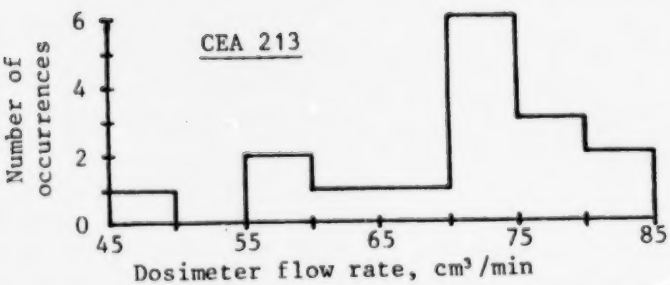



Fig. 47 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 205, 206, 208 and 209.



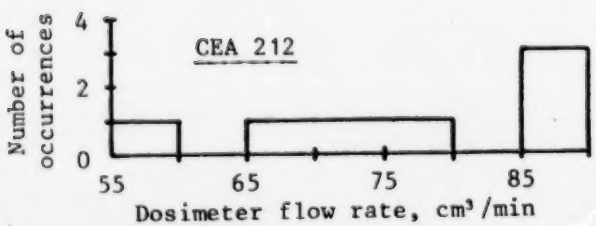
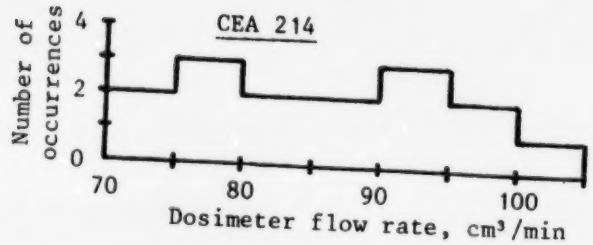
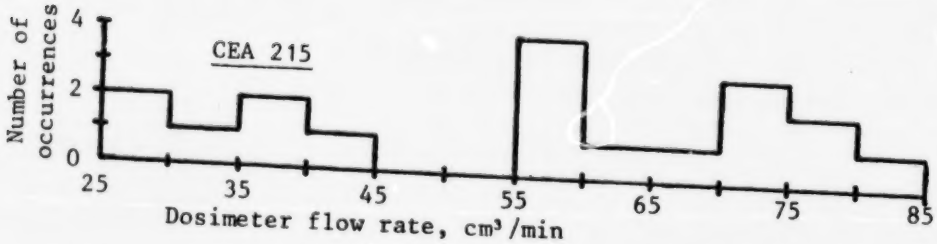
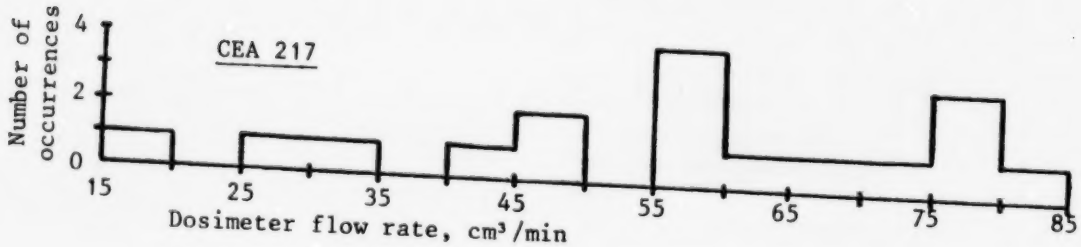




Fig. 48 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 210, 211, 213 and 212.



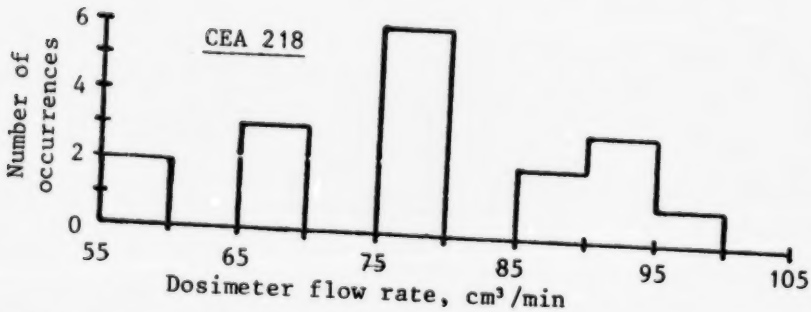




Fig. 49 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 214, 215, 217 and 218.

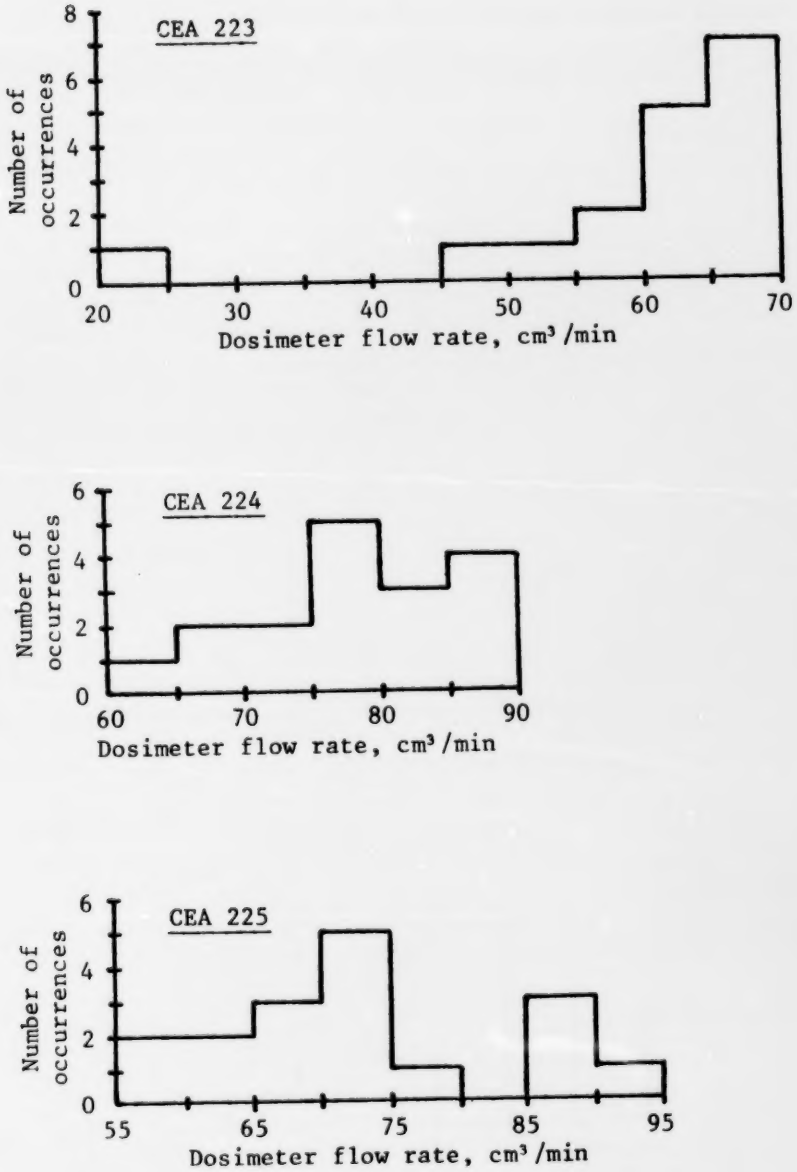



Fig. 50 - Number of occurrences versus dosimeter flow rate for track-etch dosimeters CEA 223, 224 and 225.

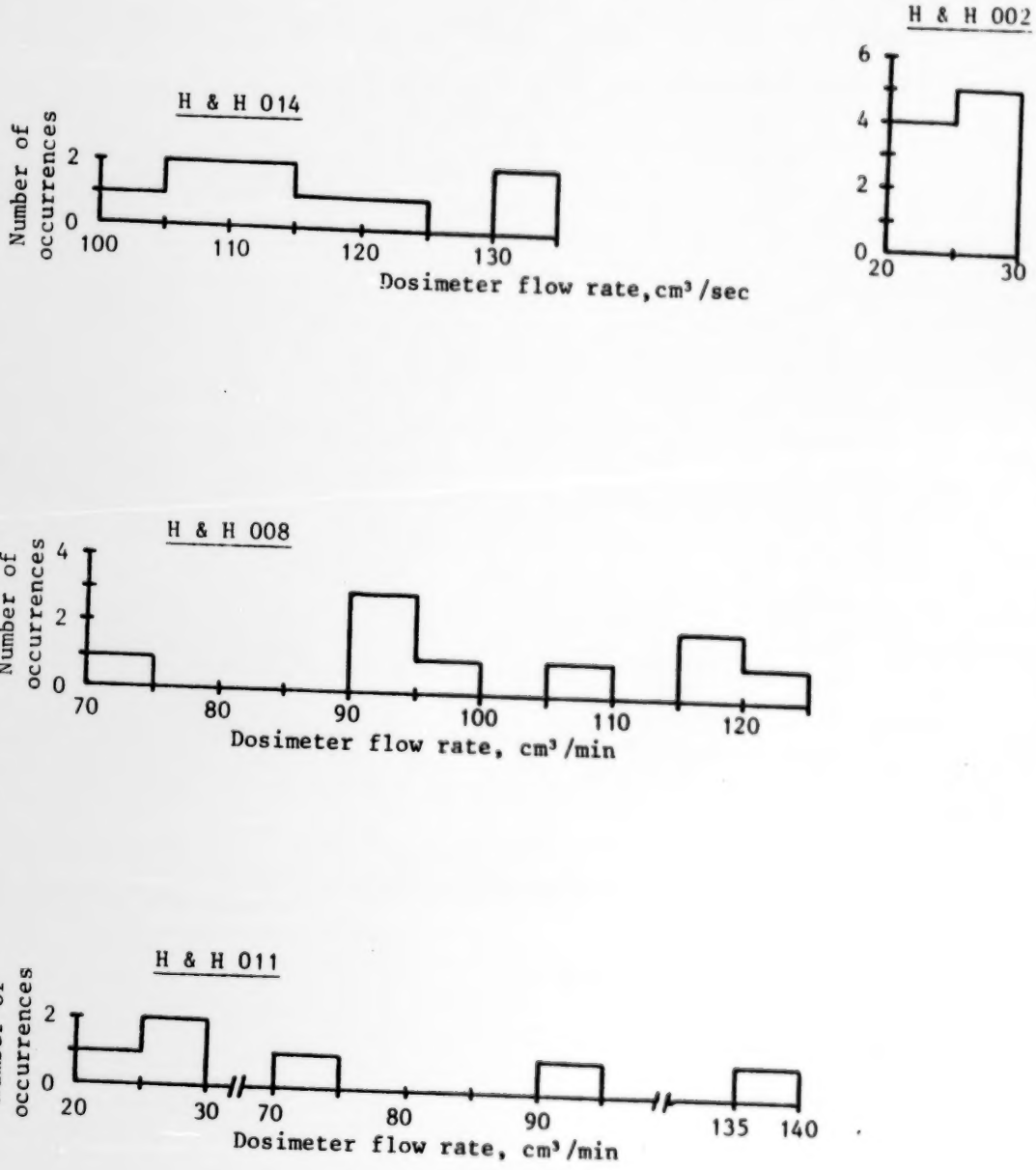



Fig. 51 - Number of occurrences versus dosimeter flow rate for H & H dosimeters H & H 014, 002, 008 and 011.

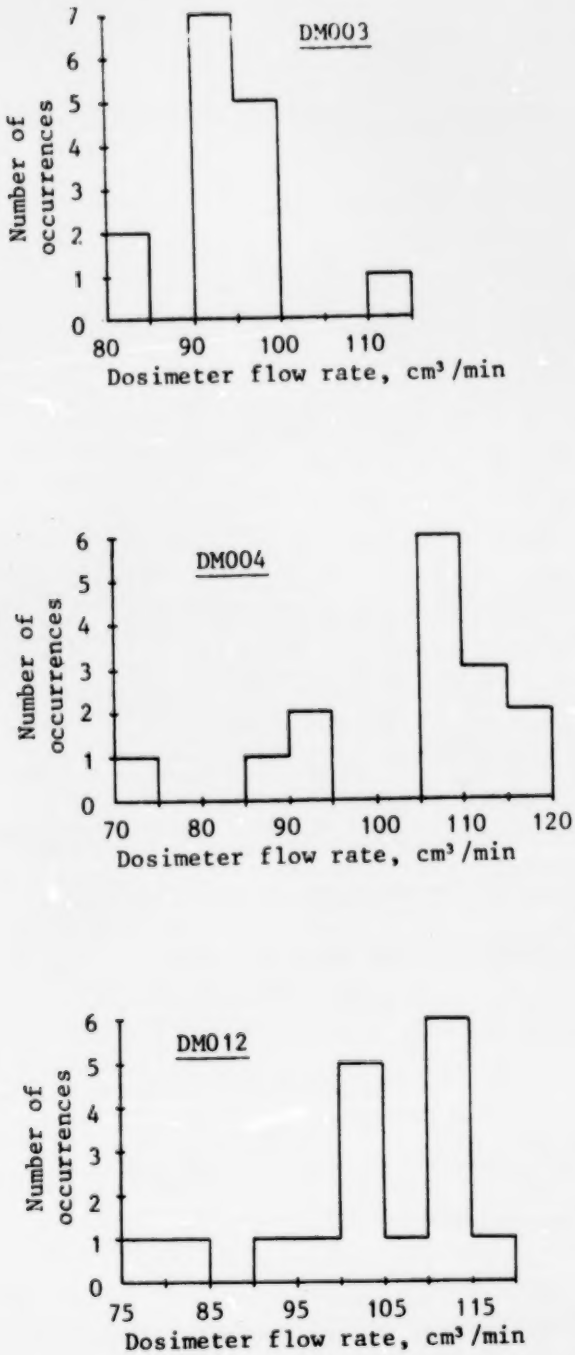



Fig. 52 - Number of occurrences versus dosimeter flow rate for α-NUCLEAR dosimeters DM003, 004 and 012.

Table 10 - Mean flow-rate and standard deviation of the flow-rate for several dosimeter prototypes (D.M.T.2).

| Dosimeter | Pump No. | Sampling Head No. | $\bar{Q}$ ($cm^3$/min) | $\sigma(Q)$ ($cm^3$/min) | $[\sigma(Q)/\bar{Q}]\times10^2$ | Average $[\sigma(Q)/\bar{Q}]\times10^2$ |
|---|---|---|---|---|---|---|
| Track-etch | 205 | 414 | 73.75 | 7.85 | 10.6 | |
| | 206 | 415 | 73.31 | 5.16 | 7.0 | |
| | 208 | 416 | 77.56 | 10.20 | 13.1 | |
| | 209 | 418 | 75.12 | 4.61 | 6.1 | |
| | 210 | 420 | 63.48 | 12.62 | 19.9 | |
| | 211 | 424 | 87.19 | 8.17 | 9.4 | |
| | 212 | 425 | 76.53 | 10.15 | 13.3 | |
| | 213 | 427 | 70.26 | 10.02 | 14.3 | 14.7 |
| | 214 | 429 | 84.05 | 8.00 | 9.5 | |
| | 215 | 430 | 57.44 | 18.22 | 31.7 | |
| | 217 | 433 | 56.87 | 18.24 | 32.1 | |
| | 218 | 450 | 76.28 | 9.54 | 12.5 | |
| | 223 | 452 | 59.16 | 10.72 | 18.1 | |
| | 224 | 453 | 78.36 | 7.19 | 9.2 | |
| | 225 | 454 | 74.31 | 10.16 | 13.7 | |
| H & H | 002 | N/A | 24.31 | 2.15 | 8.8 | |
| | 008 | N/A | 101.61 | 15.84 | 15.6 | |
| | 011 | N/A | 63.60 | 33.92 | 53.3 | 21.5 |
| | 914 | N/A | 117.44 | 9.58 | 8.2 | |
| α-Nuclear | DM003 | N/A | 94.66 | 6.60 | 7.0 | |
| | DM004 | N/A | 103.38 | 11.49 | 11.1 | |
| | DM008[1] | N/A | - | - | - | 9.3 |
| | DM012 | N/A | 103.75 | 10.09 | 9.7 | |

[1]) Not sufficient data available.

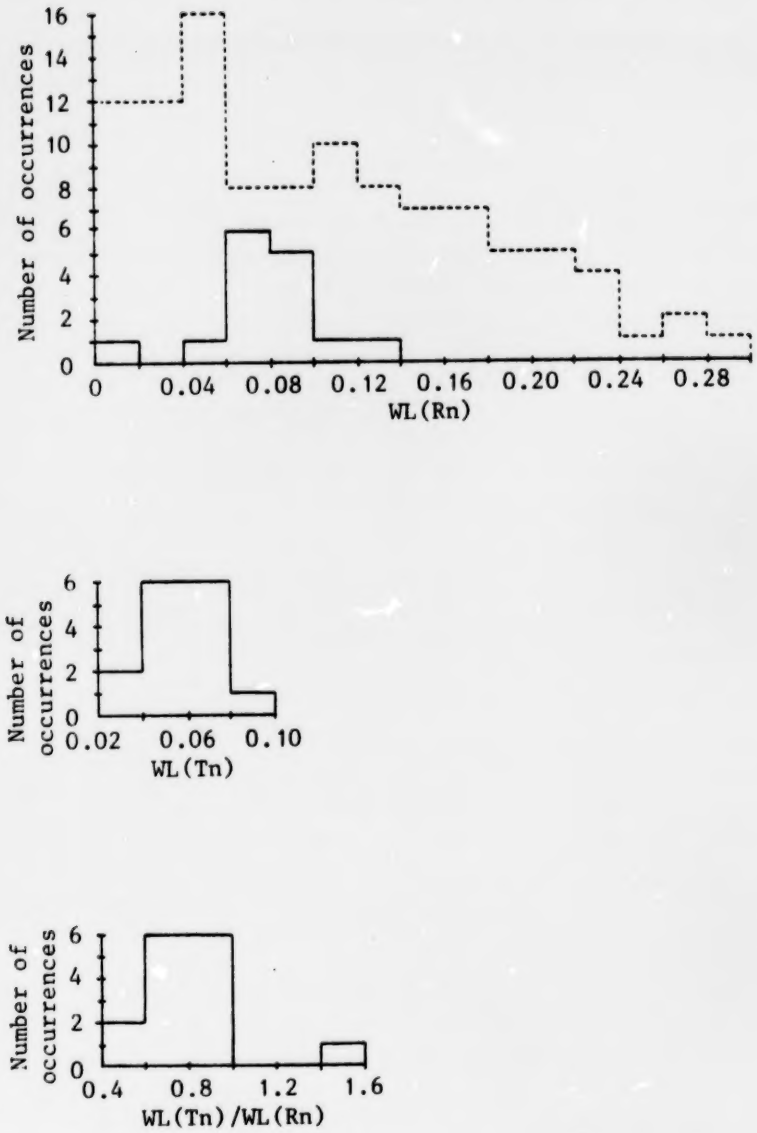



Fig. 53 - Number of occurrences versus WL(Rn), upper graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), lower graph, for track-etch dosimeters. Also shown in upper graph is WL(Rn) by grab-sampling (broken line).

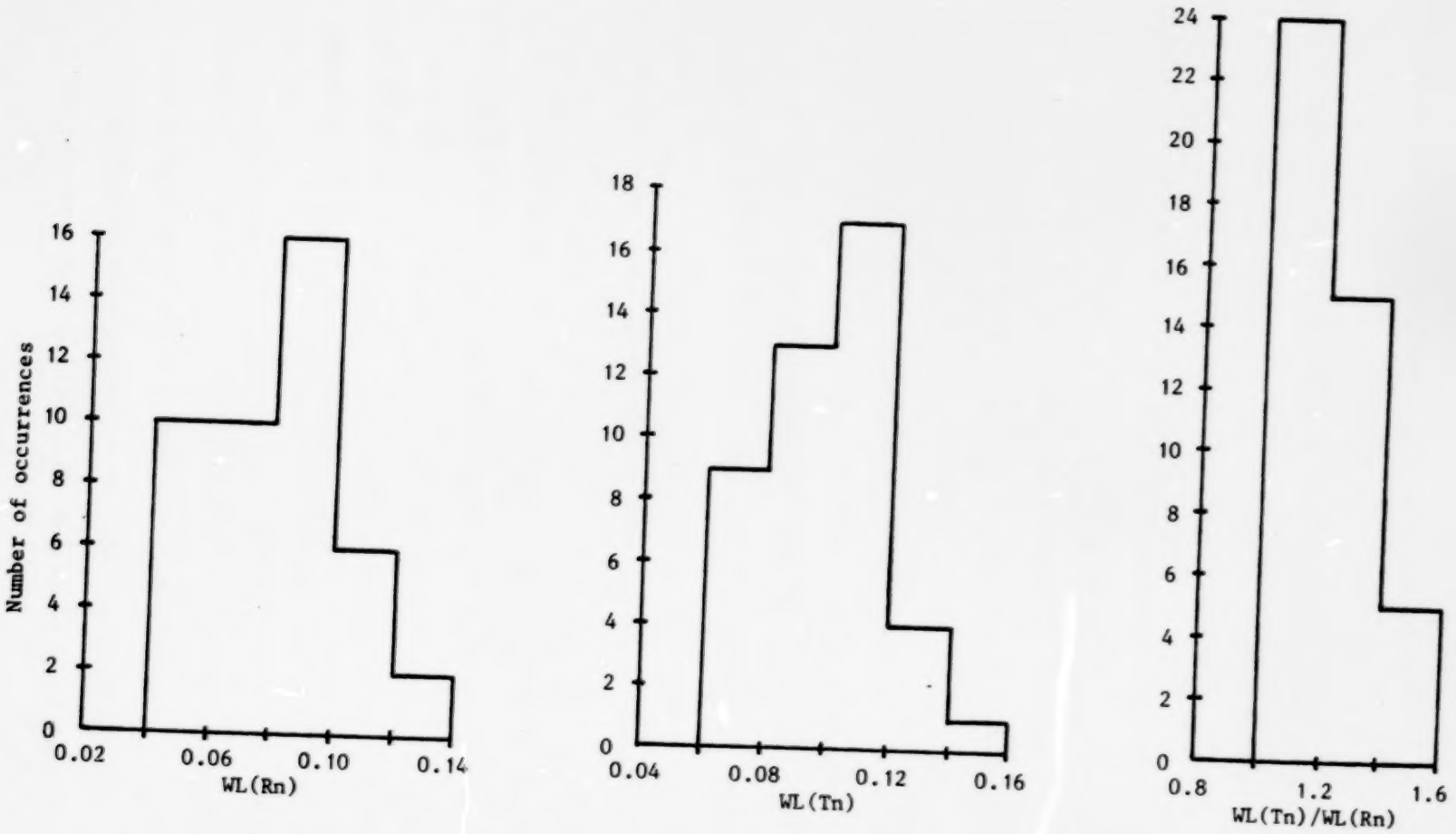



Fig. 54 - Number of occurrences versus WL(Rn), left hand side graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), right hand side graph, for α-NUCLEAR dosimeters.

WL(Rn). Most values of WL(Rn) obtained from track-etch and α-NUCLEAR dosimeters, and grab-sampling are in the range 0.06 to 0.14, 0.05 to 0.11 and 0.01 to 0.23, respectively. α-NUCLEAR dosimeters gave substantially higher values for WL(Tn) than track-etch dosimeters. Better agreement for WL(Tn) was found between α-NUCLEAR and H & H dosimeters. The ratio WL(Tn)/WL(Rn) determined by α-NUCLEAR dosimeters was substantially higher than that obtained by track-etch and H & H dosimeters (see Table 11).

Table 11 shows radiation data pertaining to the α-NUCLEAR, track-etch and H & H dosimeters. $\overline{WL}$(Rn) data in this Table indicates good agreement (within less than 10%) for α-NUCLEAR and track-etch site dosimetry (S.D.) and personal dosimetry (P.D.) dosimeters. Values for the H & H dosimeters were about half those of the other dosimeters. The Table also shows good agreement for $\overline{WL}$(Tn) for H & H and α-NUCLEAR S.D. dosimeters and for H & H and track-etch P.D. dosimeters. In terms of $\overline{WL}$(Tn)(Total), α-NUCLEAR results were substantially higher than those determined with the H & H and track-etch dosimeters. $\overline{WL}$(Rn) data from grab-sampling (≅0.12) were substantially higher than that obtained by dosimetry.

Figure 55 shows the daily grab-sampling average of WL(Rn) (based on two measurements: one in the morning; one in the afternoon) for the D.M.T.1 and D.M.T.2 tests, indicated by arrows, at the site dosimetry location. Also shown are WL(Rn) as determined by track-etch, H & H and α-NUCLEAR dosimeters. Figure 56 is identical to Fig. 55 in every respect except that WL(Tn) data instead of WL(Rn) data are shown.

Inspection of Fig. 55 indicates that WL(Rn) by grab-sampling was on the average consistently higher than that obtained by personal dosimetry. Track-etch and α-NUCLEAR data were in reasonably good agreement, but H & H data were substantially lower than data from the other two types of dosimeters.

Table 11 - Working level data for several dosimeter prototypes (D.M.T.2).

| Dosimeter | Remarks | WL(Rn) | $\overline{WL}$(Rn) | | | WL(Tn) | $\overline{WL}$(Tn) | | | $WL_T$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | S.D. | P.D. | Total[1] | | S.D. | P.D. | Total[1] | |
| H & H 002 | LiF, S.D. | 0.058 | | | | 0.10 | | | | 0.16 |
| H & H 008 | LiF, P.D. | 0.080 | | | | 0.11 | | | | 0.19 |
| H & H 011[3] | $CaF_2$, P.D. | 0.016 | 0.058 | 0.038 | 0.043 | 0.03 | 0.100 | 0.060 | 0.070 | 0.05 |
| H & H 012 | $CaF_2$, P.D. | 0.018 | | | | 0.04 | | | | 0.06 |
| DM 003 | S.D. | 0.100 | | | | 0.112 | | | | 0.212 |
| DM 004 | P.D. | 0.080 | | | | 0.101 | | | | 0.18 |
| DM 008 | S.D. | 0.098 | 0.101 | 0.073 | 0.086 | 0.117 | 0.114 | 0.100 | 0.105 | 0.215 |
| DM 012 | P.D.[2] | 0.076 | | | | 0.090 | | | | 0.167 |
| Track-etch[4] | - | 0.079 | 0.097 | 0.077 | 0.079 | 0.059 | 0.067 | 0.058 | 0.059 | 0.138 |
| Grab-sampling | | 0.120 | | | | | | | | |

[1]) indicates the average value obtained with all dosimeters tested, i.e. P.D. plus S.D.

[2]) mostly P.D.

[3]) large flow-rate variations.

[4]) all S.D. dosimeters, or all P.D. dosimeters, or all dosimeters. Note: S.D. and P.D. stand for dosimeters used for site dosimetry and personal dosimetry, respectively.

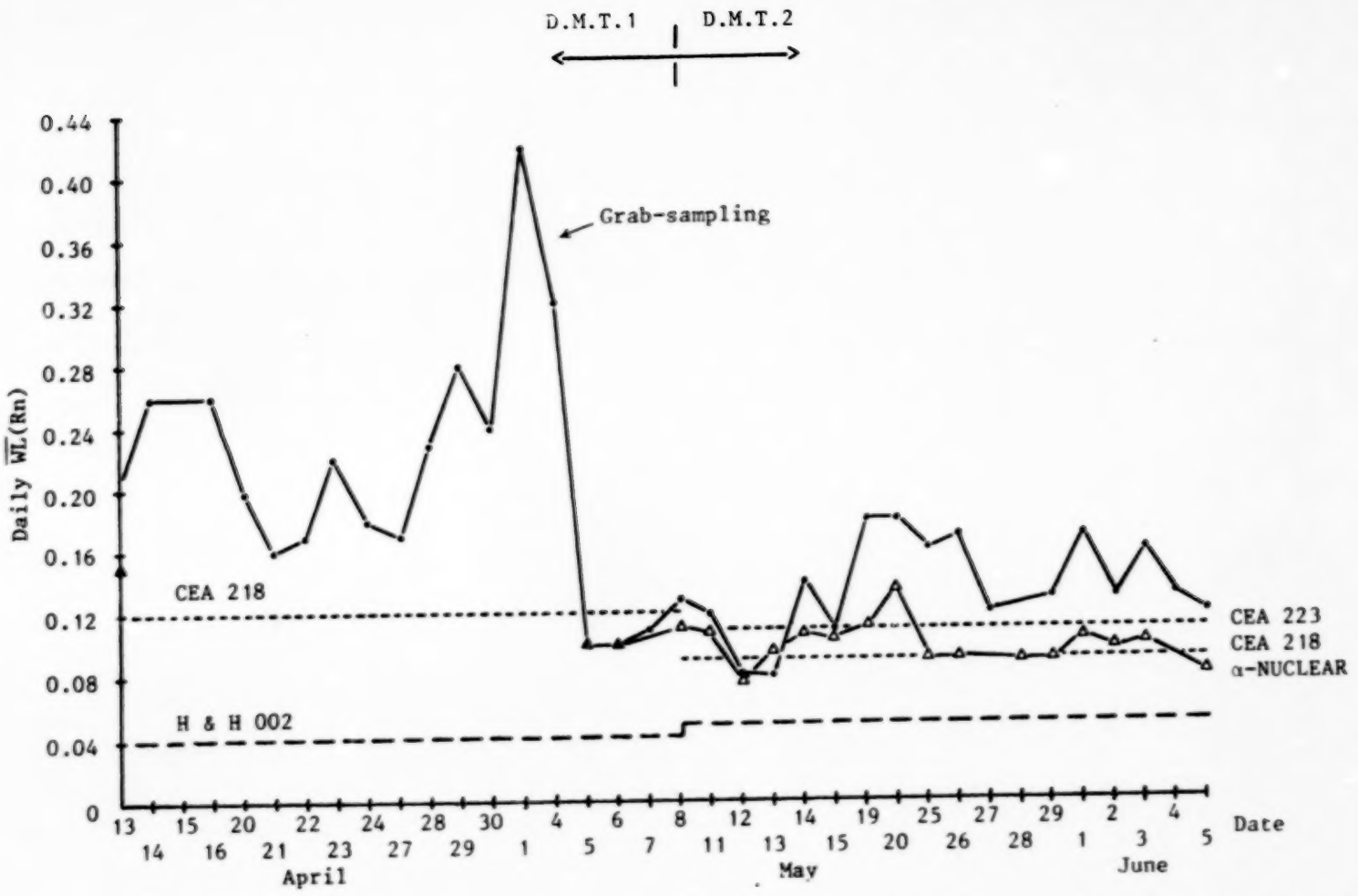



Fig. 55 - Daily $\overline{WL}$(Rn) versus date by grab-sampling (-·-) and α-NUCLEAR dosimeters (-Δ-). Also shown in the graph are the average values of WL(Rn) as determined by track-etch dosimeters (---) and H & H dosimeters (– –). Data from two different tests: D.M.T.1 and D.M.T.2, indicated by arrows.

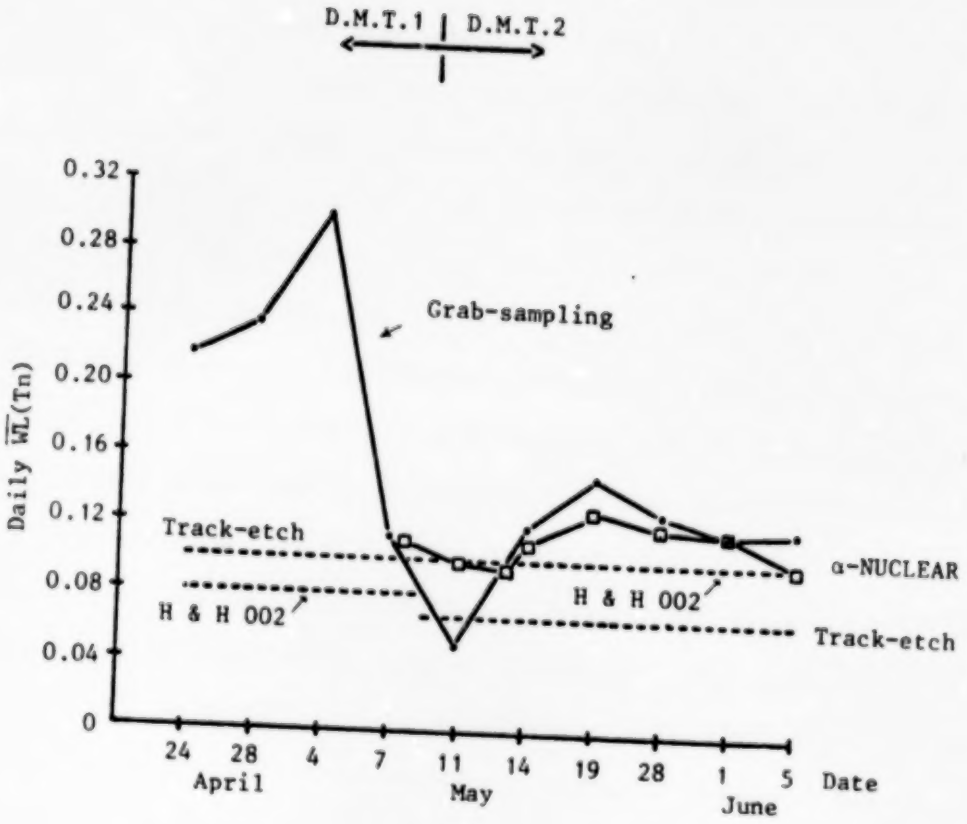



Fig. 56 - Daily $\overline{WL}$(Tn) versus date by grab-sampling (-·-) and α-NUCLEAR dosimeters (-□-). Also shown in the graph are the average values of WL(Tn) as determined by the track-etch and H & H 002 dosimeters (broken lines). Data from two different tests: D.M.T.1 and D.M.T.2.

As previously indicated, track-etch and H & H data are based on two WL determinations, one WL(Rn) and one WL(Tn), per dosimeter for each test, whereas α-NUCLEAR dosimeters are read daily. Because of this, track-etch and H & H data only represent long-term average values precluding dynamic conditions to be investigated, a unique feature of α-NUCLEAR dosimeters. Because of this feature, daily WL fluctuations on a daily basis can be followed and compared with grab-sampling data. As Fig. 55 indicates, the α-NUCLEAR dosimeters followed grab-sampling measurements quite closely.

Inspection of Fig. 56 for test D.M.T.2 shows good agreement between WL(Tn) data from α-NUCLEAR dosimeters and grab-sampling, and only fair agreement between the latter and H & H dosimeters. Track-etch dosimeters gave substantially lower values. For test D.M.T.1, grab-sampling data were appreciably higher than data from track-etch and H & H dosimeters, the latter (H & H) lying lower than the track-etch, an experimental fact which is consistent with WL(Rn) data for D.M.T.1 (see Fig. 55) and which is not, at present, clearly understood. Again α-NUCLEAR dosimeters followed quite closely the grab-sampling daily WL(Tn) profile for D.M.T.2.

For a variety of reasons there are insufficient data from test D.M.T.1 for a reliable comparison between grab-sampling and α-NUCLEAR dosimeters. One reason is that the initial few days of D.M.T.1 were spent as part of the staff training program in order to get acquainted with the logistics of implementing an underground personal dosimetry program. Hence, a number of errors and mistakes were to be expected. Furthermore, some instrument malfunction, similar to the kind reported at Rio Algom, compounded by operator errors in operating and programing the α-NUCLEAR reader, contributed to the loss of valuable data.

## D.M.T.3 SITE DOSIMETRY TESTS: EXPERIMENTAL RESULTS AND DISCUSSION

This test was conducted in an area adjacent to a crusher, and hence, under heavy dust conditions. The test was intended for dosimeter calibration purposes. Grab-sampling measurements were done as frequently as practically possible during the day-shift. Fifteen track-etch dosimeters and three α-NUCLEAR dosimeters were used. H & H dosimeters were not included in this test because of their poor pump performance in previous tests.

Figure 57 shows histograms of the frequency of occurrence for which the ratios [RaB]/[RaA] and [RaC]/[RaA] have values within a given range. Most values for the ratio [RaB]/[RaA] are in the range 0.45 to 0.7 with a maximum around 0.55. Similarly, values for the ratio [RaC]/[RaA] are mostly in the range 0.3 to 0.5 with a maximum at about 0.35. A distribution of the above ratios in a diagram showing the theoretical ratios as predicted by three different mine models is shown in Fig. 58. (Note: for an explanation of the meaning of this graph see Rio Algom data.) The data of Fig. 57 and 58 are plotted in Fig. 59 in terms of [RaA]/WL(Rn) and [RaB]/WL(Rn), where WL(Rn) refers to the WL as determined by grab-sampling. Figure 59 shows that the age of air corresponding to the area where measurements were carried out was between 30 min and 50 min according to the classical mine model.

Figures 60, 61 and 62 show histograms of WL(Rn), WL(Tn) and WL(Tn)/WL(Rn) for the measurements carried out, respectively, by grab-sampling, α-NUCLEAR dosimeters and track-etch dosimeters (some more data are shown in Table 12). In general, much narrower ranges were found for the above variables by track-etch dosimetry than with grab-sampling. A seemingly better agreement with grab-sampling was found by α-NUCLEAR dosimetry than by track-etch dosimetry. In particular, a wide range of values was found for WL(Rn) and WL(Tn) by grab-sampling which is partly confirmed by the α-NUCLEAR dosimeters, but which is not reflected by track-etch dosimetry.

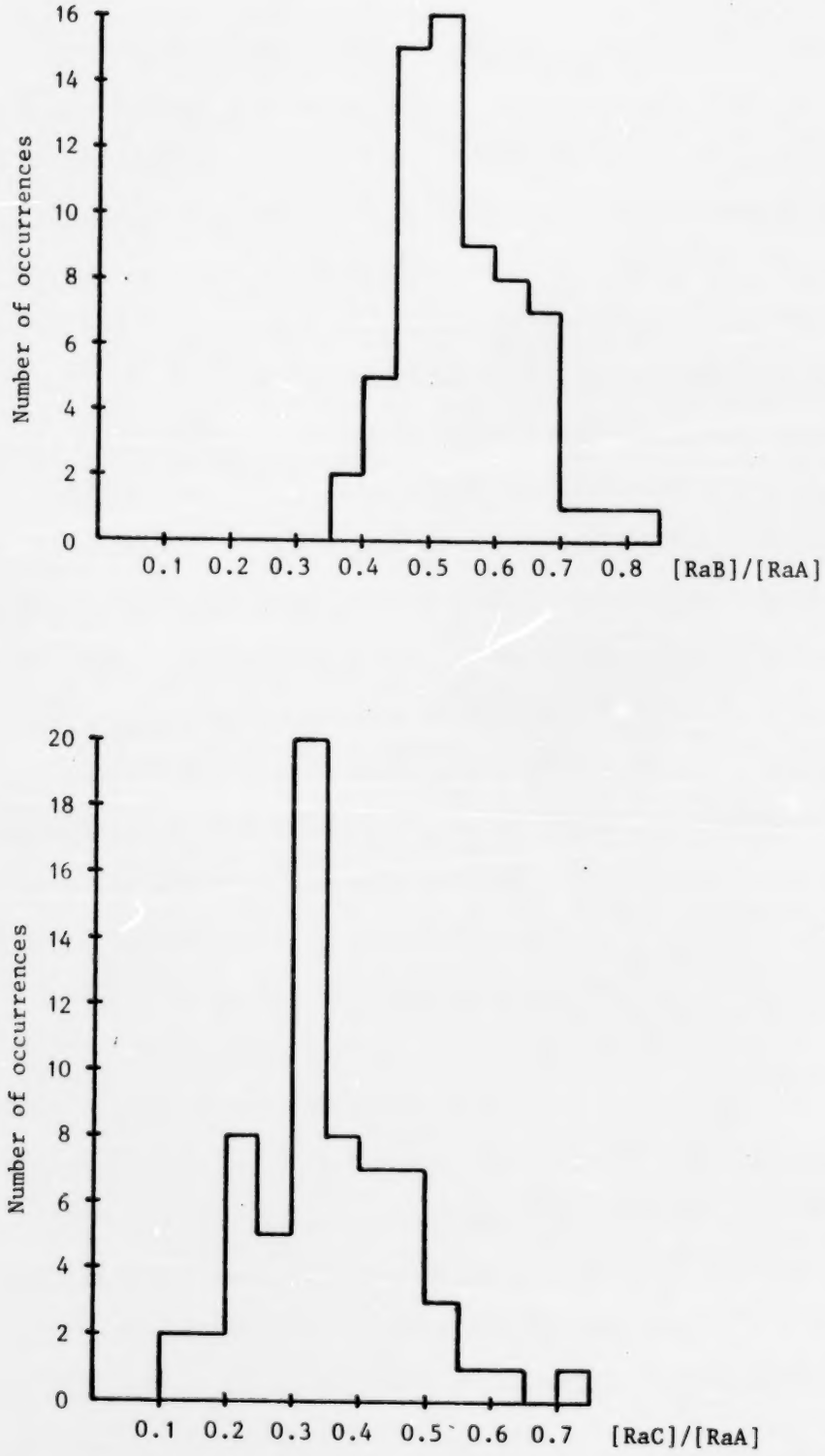



Fig. 57 - Number of occurrences versus the ratios [RaB]/[RaA] and [RaC]/[RaA] from field data.

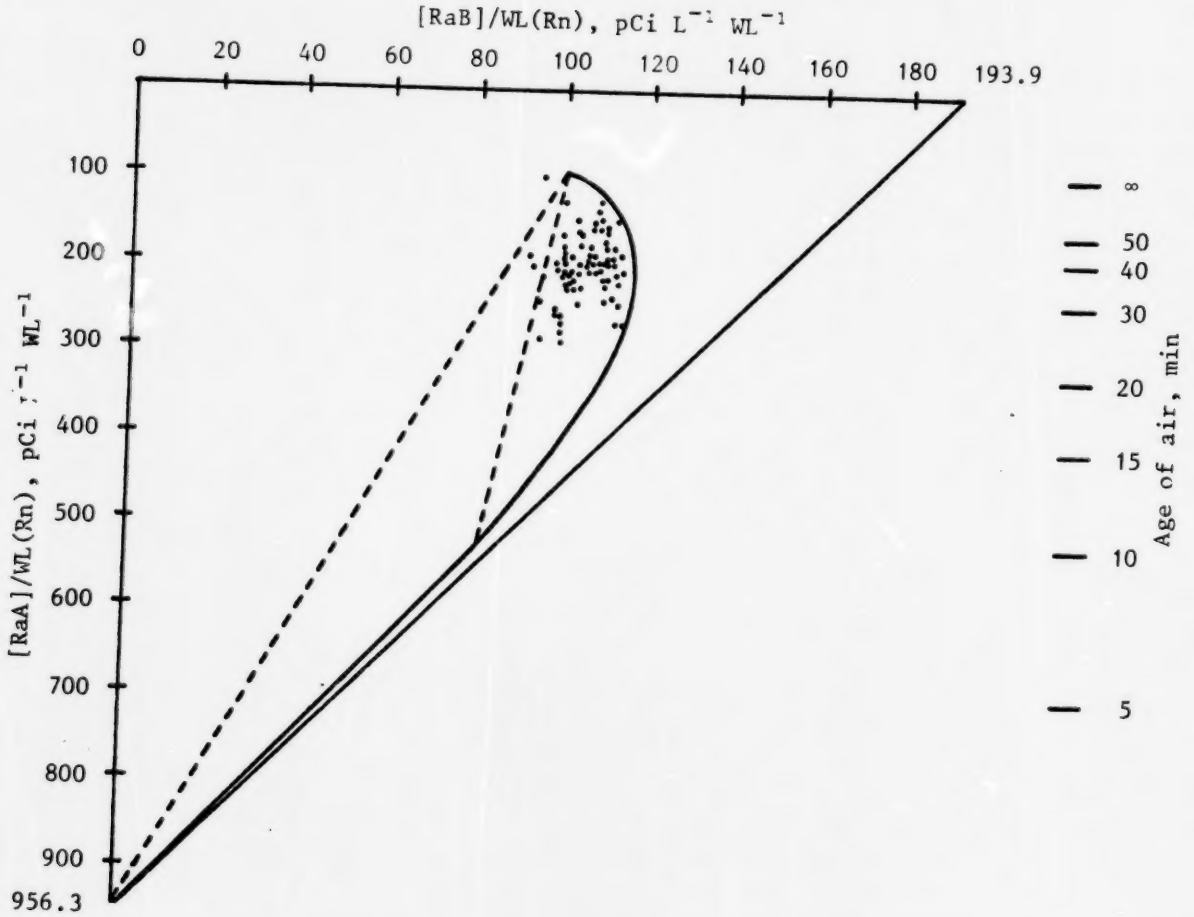



Fig. 58 - Experimental [RaB]/WL(Rn) versus experimental [RaA]/WL(Rn) (dots) in a graph showing the theoretical values for the same ratios according to the isolated mine model (full and broken lines).

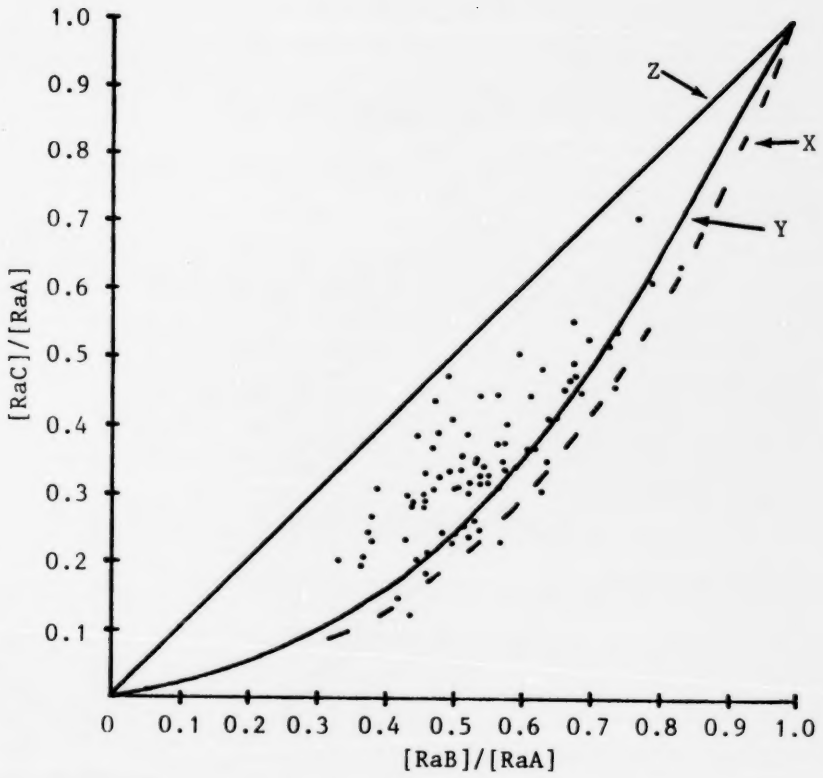
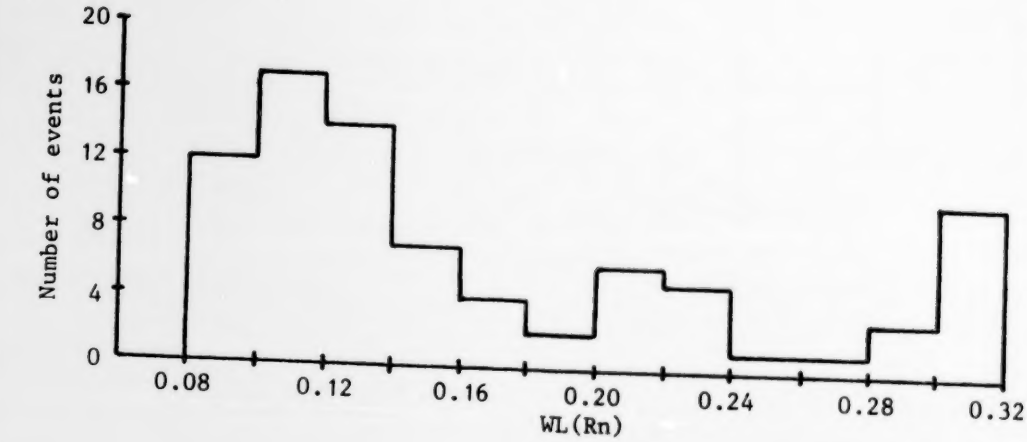
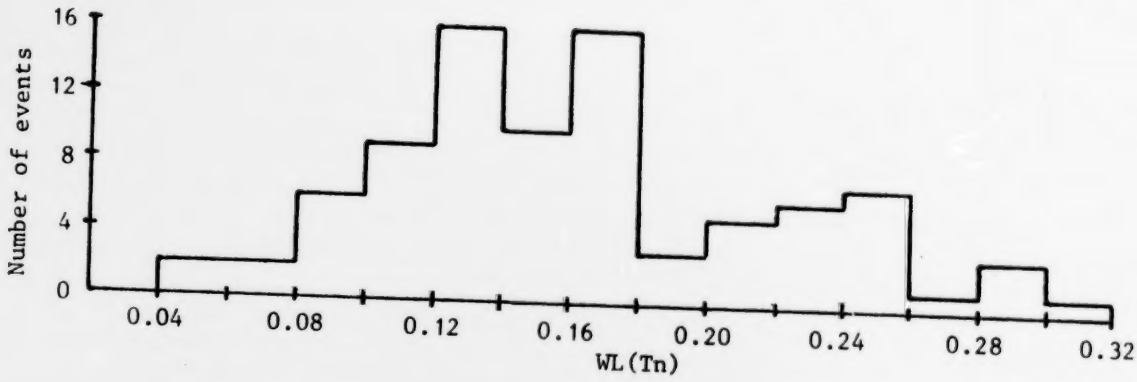



Fig. 59 - Experimental [RaC]/[RaA] versus experimental [RaB]/[RaA], dots, in a graph showing the theoretical boundaries for the same ratios according to the isolated mine model (X), the mine tunnel model (Y) and a model consisting of the mixing of 'young' air and 'old' air (Z).



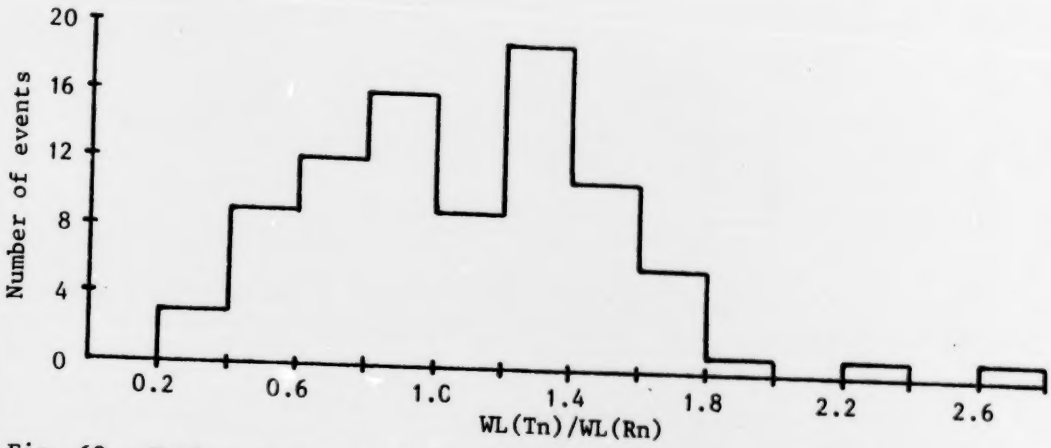




Fig. 60 - Number of events versus WL(Rn), upper graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), lower graph, for grab-sampling. (Note: events and occurrences are used interchangeably in this report.)

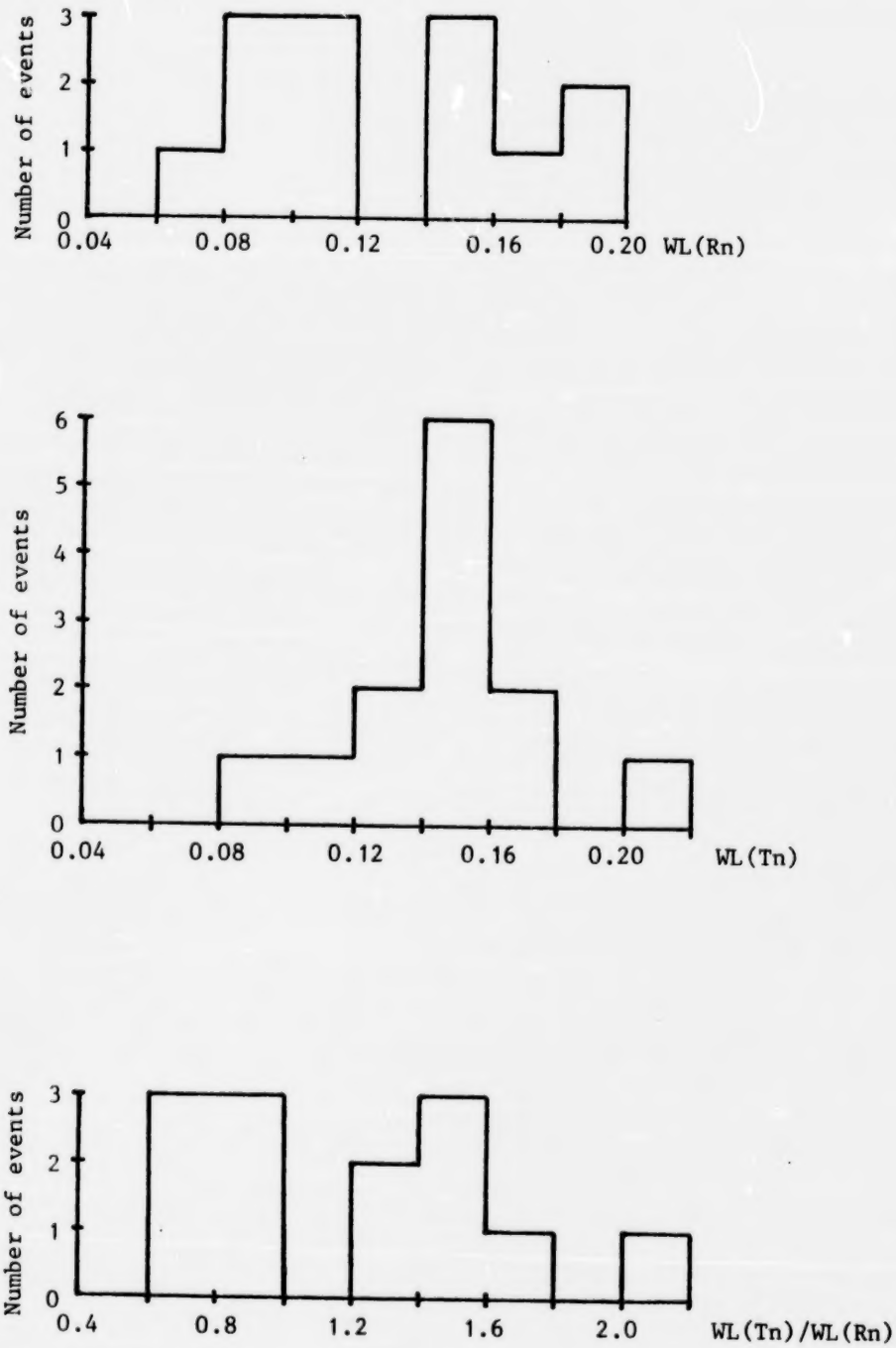



Fig. 61 - Number of events versus WL(Rn), upper graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), lower graph for α-NUCLEAR dosimeters.

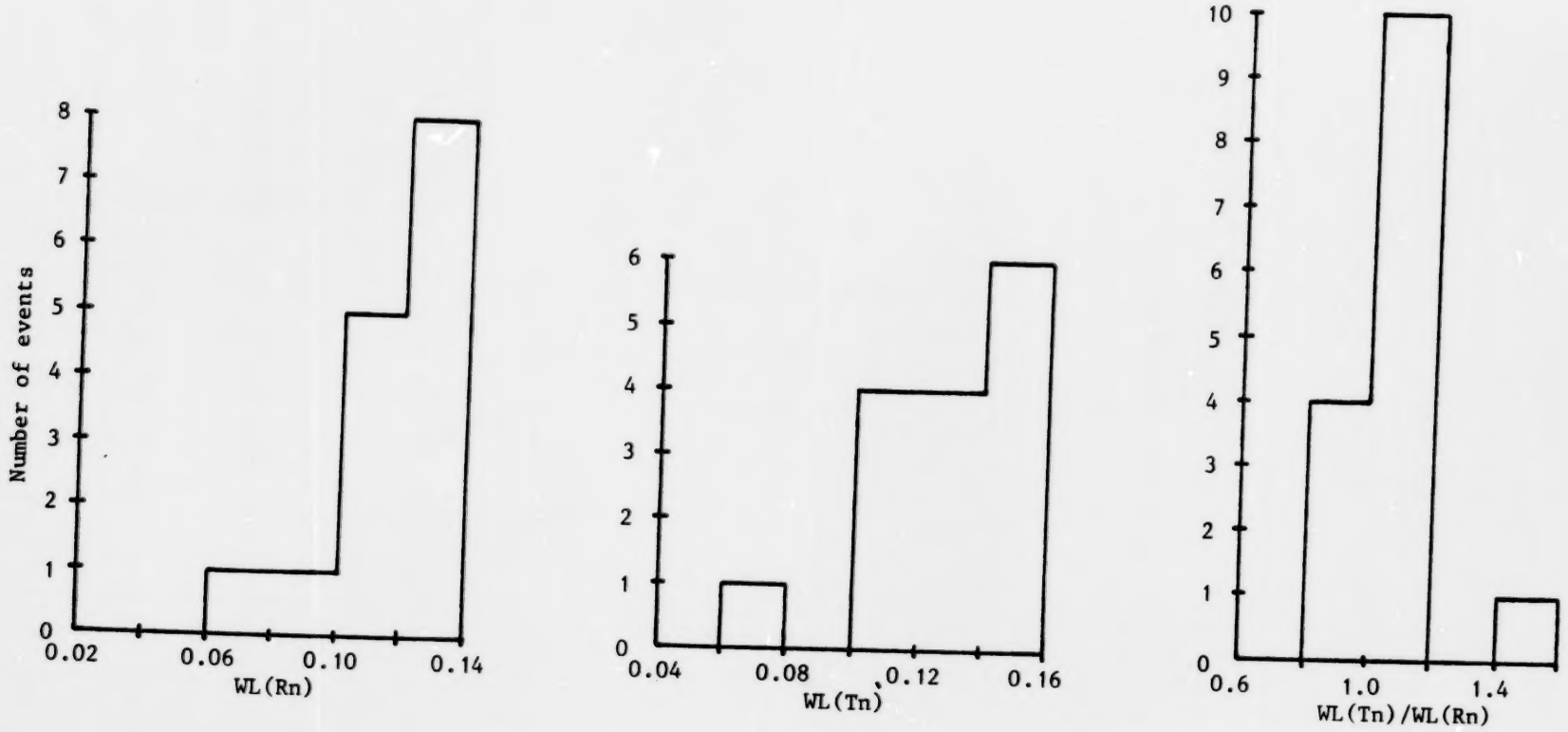



Fig. 62 - Number of events versus WL(Rn), left hand side graph; WL(Tn), middle graph; and WL(Tn)/WL(Rn), right hand side graph, for track-etch dosimeters.

Table 12 - Some working level data (D.M.T.3).

| Date | $\overline{WL}$(Rn) | $\overline{WL}$(Tn) | $\overline{WL}$(Tn)[1] | $\overline{WL}$(Rn) (α-Nuclear) | $\overline{WL}$(Tn) (α-Nuclear) | $\overline{WL}$(Rn) (Track-etch) | $\overline{WL}$(Tn) (Track-etch) |
|---|---|---|---|---|---|---|---|
| June 16 | 0.227 | 0.207 | 0.113 | 0.16 | 0.16 | | |
| June 17 | 0.234 | 0.189 | 0.115 | 0.18 | 0.14 | | |
| June 18 | 0.129 | 0.176 | 0.117 | 0.09 | 0.12 | 0.118 | 0.126 |
| June 19 | 0.161 | 0.171 | - | 0.10 | 0.18 | | |
| June 22 | 0.156 | 0.168 | 0.107 | 0.10 | 0.14 | | |

[1]) data obtained with WL meter Pylon 1000B.

Figure 63 shows a calibration of three α-NUCLEAR dosimeters (DM003, DM004 and DM012) similar to the calibration conducted at Rio Algom. The average value of the ratio $N_\alpha$/WLH is 24342 α-counts $WLH^{-1}$ which agrees fairly well (within 12%) with the average value of 21600 α-counts $WLH^{-1}$ previously obtained at Rio Algom for the dosimeters DM008 and DM012. If a dosimeter flow-rate, Q, of 0.1 L/min is taken, the $K_f$ factor becomes 243.3, which again agrees quite well with previously determined values at Rio Algom. (Note: the calibration indicated above has been carried out for the three dosimeters together. Individual calibrations can easily be obtained by means of Fig. 63 which contains all pertinent data.)

Figure 64 shows a comparison of daily average values of WL(Rn) and WL(Tn) by grab-sampling and values determined by track-etch and α-NUCLEAR dosimetry. In general, and as already pointed out, the α-NUCLEAR dosimeters followed grab-sampling WL-profiles quite closely. The values of WL(Rn) and WL(Tn) as determined by track-etch and α-NUCLEAR dosimetry were lower than those for grab-sampling. Better agreement was found with α-NUCLEAR dosimeters than with track-etch dosimeters.

## D.M.T.4 PERSONAL DOSIMETRY: EXPERIMENTAL RESULTS AND DISCUSSION

The fourth and last test at Denison Mines was conducted in the leaching section. This is an area of relatively high radiation levels, highly variable from place to place, and where workers wear airstream type respirators for protection. Because of the limited number of workers making up the leaching crew, only six track-etch dosimeters and one α-NUCLEAR dosimeter were used Five track-etch dosimeters were given to the leaching crew, whereas the environmental technician in charge of carrying out WL measurements wore one track-etch and one α-NUCLEAR dosimeter. (During the test one track-etch dosimeter broke down and was removed from the test and replaced with another

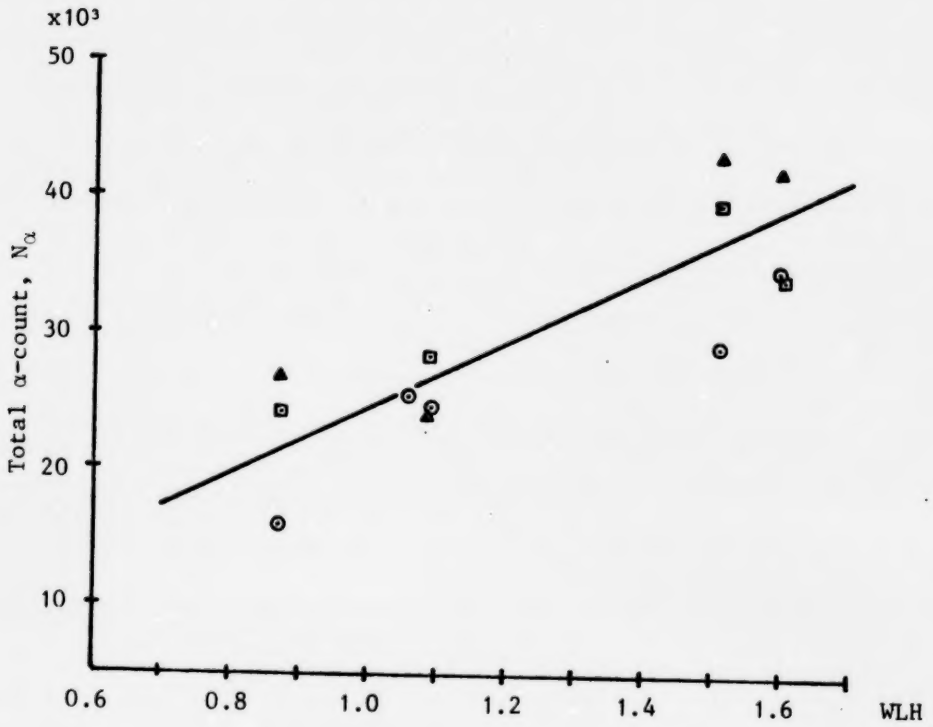



Fig. 63 - Total α-count versus WLH for α-NUCLEAR dosimeters DM003 (⊙), DM004 (⊡) and DM012 (▲). Average ratio $N_\alpha$/WLH calculated from above graph (best fitted line by linear regression analysis) is 24342 counts $WLH^{-1}$.

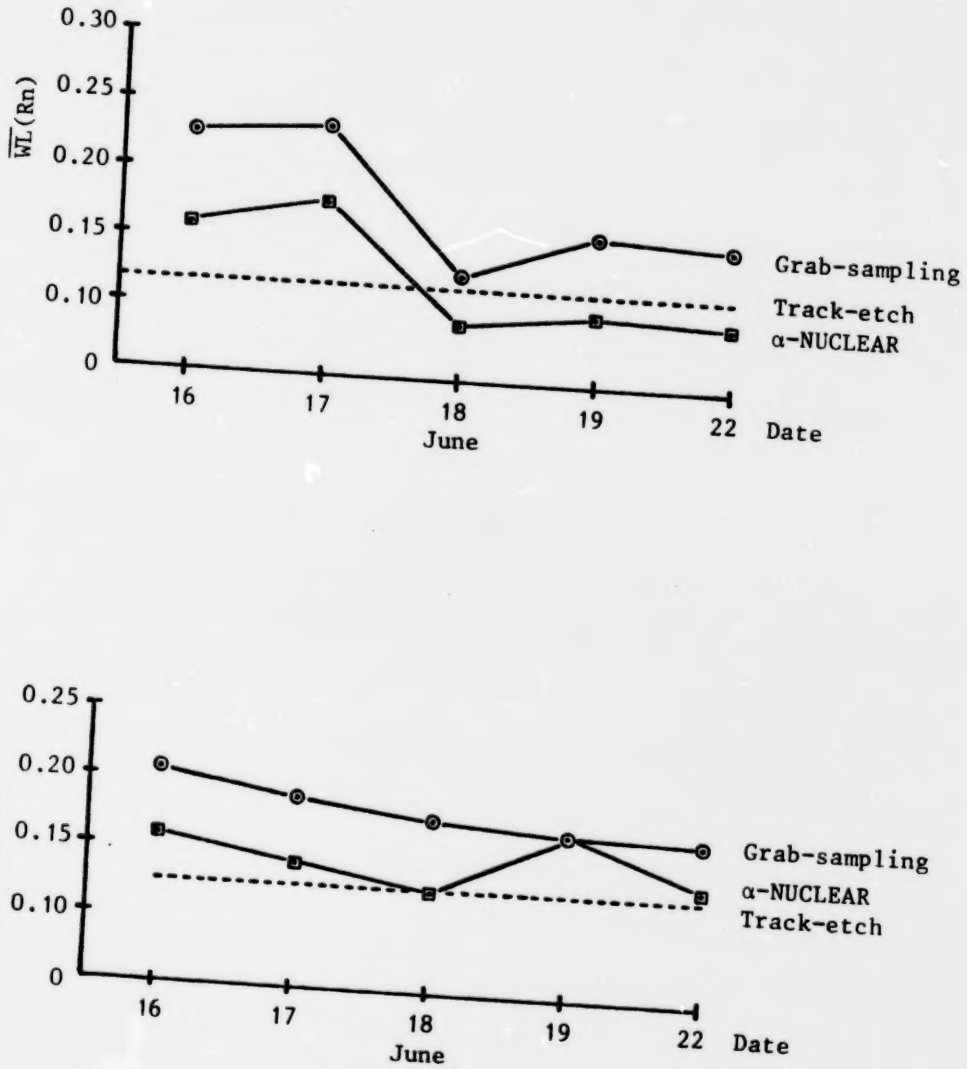



Fig. 64 - Daily $\overline{WL}$(Rn) versus date, upper graph, and $\overline{WL}$(Tn) versus date, lower graph, for grab-sampling (⊙) and α-NUCLEAR dosimeters (⊡). Also shown in the graphs is the average WL(Rn) and WL(Tn) as determined by track-etch dosimeters (---).

one.) The latter arrangement ensured a study, as close as possible, of the response of the track-etch and α-NUCLEAR dosimeters under the highly variable environmental conditions of the test. It also provided a means for direct comparison of the dosimeters. No site dosimetry was conducted in this test. No H & H dosimeters were used because of their poor pump performance exhibited in previous tests. The duration of the D.M.T.4 was 2-weeks.

The leaching section was located quite far from the 'cage'. On an average it took about one-hour travel time to get from the cage to the working site and vice versa. Because of the long travel time involved through mine sections of widely different environmental conditions, the analysis of the data was particularly difficult. Monitoring of the WL covered waiting areas, travel routes, the lunch room and the working area.

Figure 65 shows flow-rate histograms for the track-etch and α-NUCLEAR dosimeters. Flow-rate fluctuations for the track-etch dosimeters were significant although below 30%. The only α-NUCLEAR dosimeter tested (DM004) showed flow fluctuations of less than 20% over the two-week period of the underground test. More relevant data pertaining to flow-rates are given in Table 13.

Figure 66 shows WL(Rn) and WL(Tn) histograms for grab-sampling, and α-NUCLEAR and track-etch dosimeters. No firm conclusions can be drawn from the comparison of α-NUCLEAR and track-etch dosimeter results because of insufficient data. However, the WL(Rn) distribution as determined by grab-sampling indicate much higher values than those obtained by track-etch and α-NUCLEAR dosimeters. This is to be expected because:

a) Extreme variability of the WL(Rn) in the areas surveyed, i.e., quite high although variable WL(Rn) in the leaching section, and moderate to low WL(Rn) in travel routes, waiting areas and lunch room;

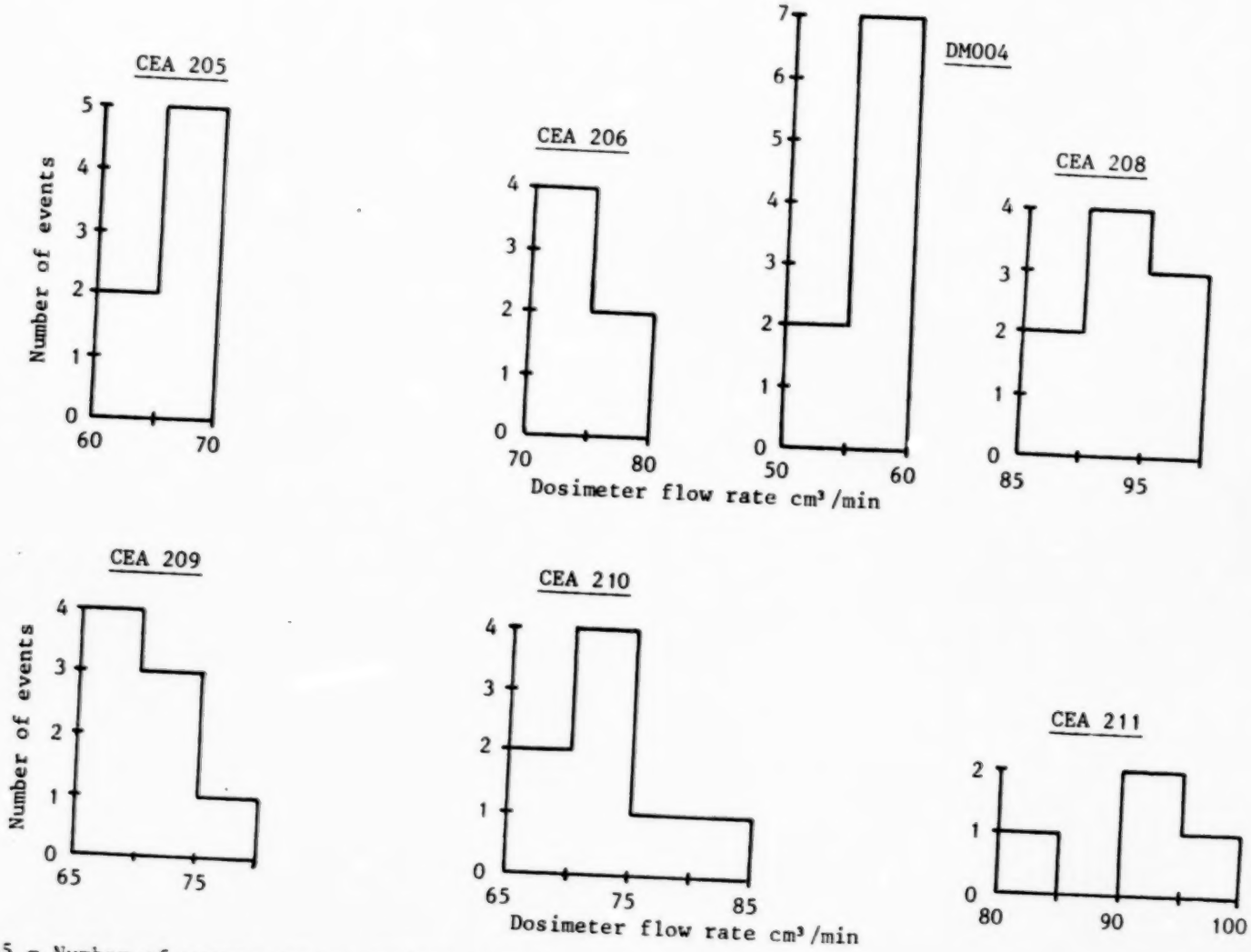



Fig. 65 - Number of events versus dosimeter flow rate for track-etch dosimeters CEA 205, 206, 208, 209, 210 and 211, and α-NUCLEAR dosimeter DM004.

Table 13 - Mean flow-rate and standard deviation of the flow-rate for several dosimeter prototypes (D.M.T.4).

| Dosimeter | Pump No. | Sampling Head No. | $\bar{Q}$ ($cm^3/min$) | $\sigma(Q)$ ($cm^3/min$) | $(\sigma(Q)/\bar{Q}) \times 10^2$ |
|---|---|---|---|---|---|
| Track-etch | 205 | 414 | 76.58[1] | 29.73 | 38.8 |
| | 206 | 415 | 74.01 | 2.33 | 3.1 |
| | 208 | 416 | 93.26 | 4.06 | 4.3 |
| | 209 | 418 | 70.65 | 3.91 | 5.5 |
| | 210 | 420 | 73.85 | 5.68 | 7.7 |
| | 211 | 424 | 90.48 | 5.51 | 6.1 |
| α-Nuclear | DM 004 | N/A | 57.36 | 2.52 | 4.3 |

[1]) One flow-rate measurement substantially higher than the rest. It might be an experimental error.

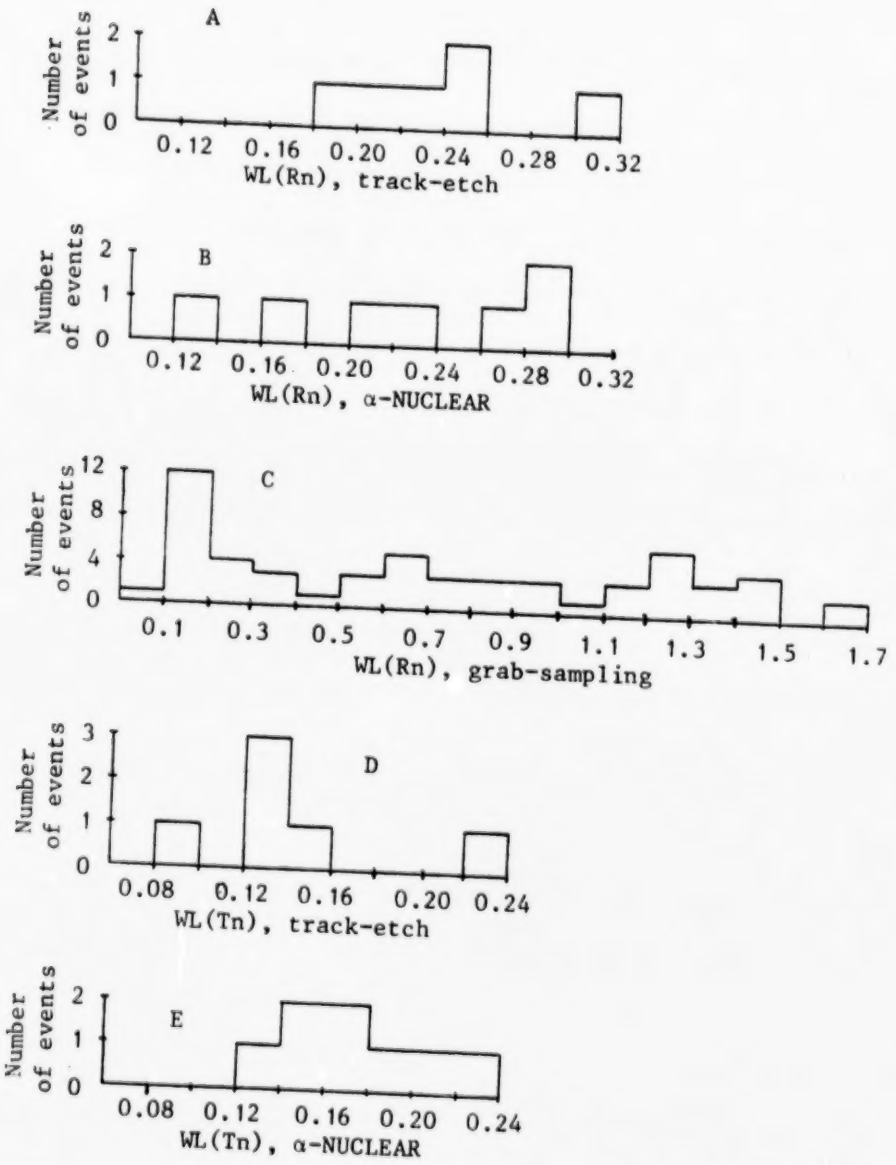



Fig. 66 - Number of events versus WL(Rn) for track-etch dosimeters (A), α-NUCLEAR dosimeters (B) and grab-sampling (C). Also shown is number of events versus WL(Tn) for track-etch dosimeters (D) and α-NUCLEAR dosimeters (E).

b) Long time spent in areas other than the working areas, i.e., approximately 1 to 3 hours;

c) Averaging characteristics of personal α-dosimeters.

Figures 67 and 68 show the daily average WL(Rn) as determined by grab-sampling, the average WL(Rn) over the two weeks of underground testing, i.e., G.S.$\overline{WL}$(Rn), and the readings obtained from the track-etch and α-NUCLEAR dosimeters. The Figures show the high variability of the daily average WL(Rn), up to a factor of 4 between maximum and minimum. Furthermore, the Figures indicate that all dosimeters gave lower WL(Rn) than that determined by grab-sampling, confirming previous observations. From this test, one may also conclude that,on the average,both dosimeters underestimated WL(Rn), in relation to grab-sampling, by about the same amount (about 30%). Figure 68 also shows that the α-NUCLEAR dosimeter followed the grab-sampling WL(Rn) quite closely, an experimental fact that has been previously reported.

## STUDY OF FLOW-RATE VARIATIONS AND SPECTRAL CHANGES CAUSED BY FILTER LOADING (RIO ALGOM AND DENISON MINES)

Under continuous operation,filters accumulate an appreciable amount of airborne particles, such as quartz dust, diesel particulates, oil mists and water vapour. Particulate accumulation, i.e., filter loading, may affect the dosimeter performance in a number of ways:

1) by effectively clogging the filter, totally or partially, thereby impeding or reducing the rate of air-flow through it;
2) by absorbing α-particles in the thickness of the deposited particulates;
3) by shifting the energy of the emerging α-particles from the otherwise clean filter.

Items (1) to (3) effectively reduce the efficiency and performance of the dosimeter. Several experiments were carried out to determine the extent of the above effects.

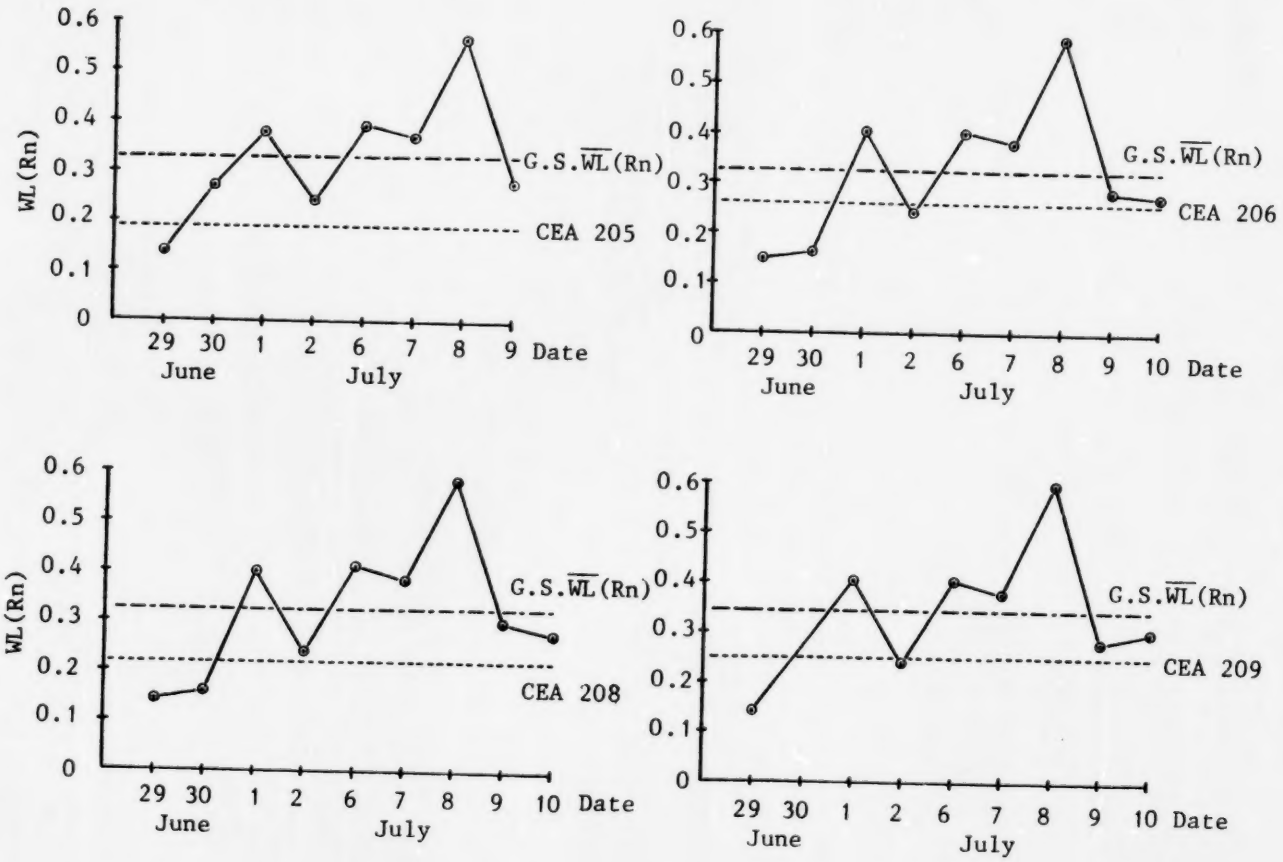



Fig. 67 - Daily average WL(Rn) versus date for grab-sampling (⊙). Also shown is the overall $\overline{WL}$(Rn) by grab-sampling (-·-), indicated by G.S.$\overline{WL}$(Rn)) and by track-etch dosimeters (---) CEA 205, 206, 208 and 209.

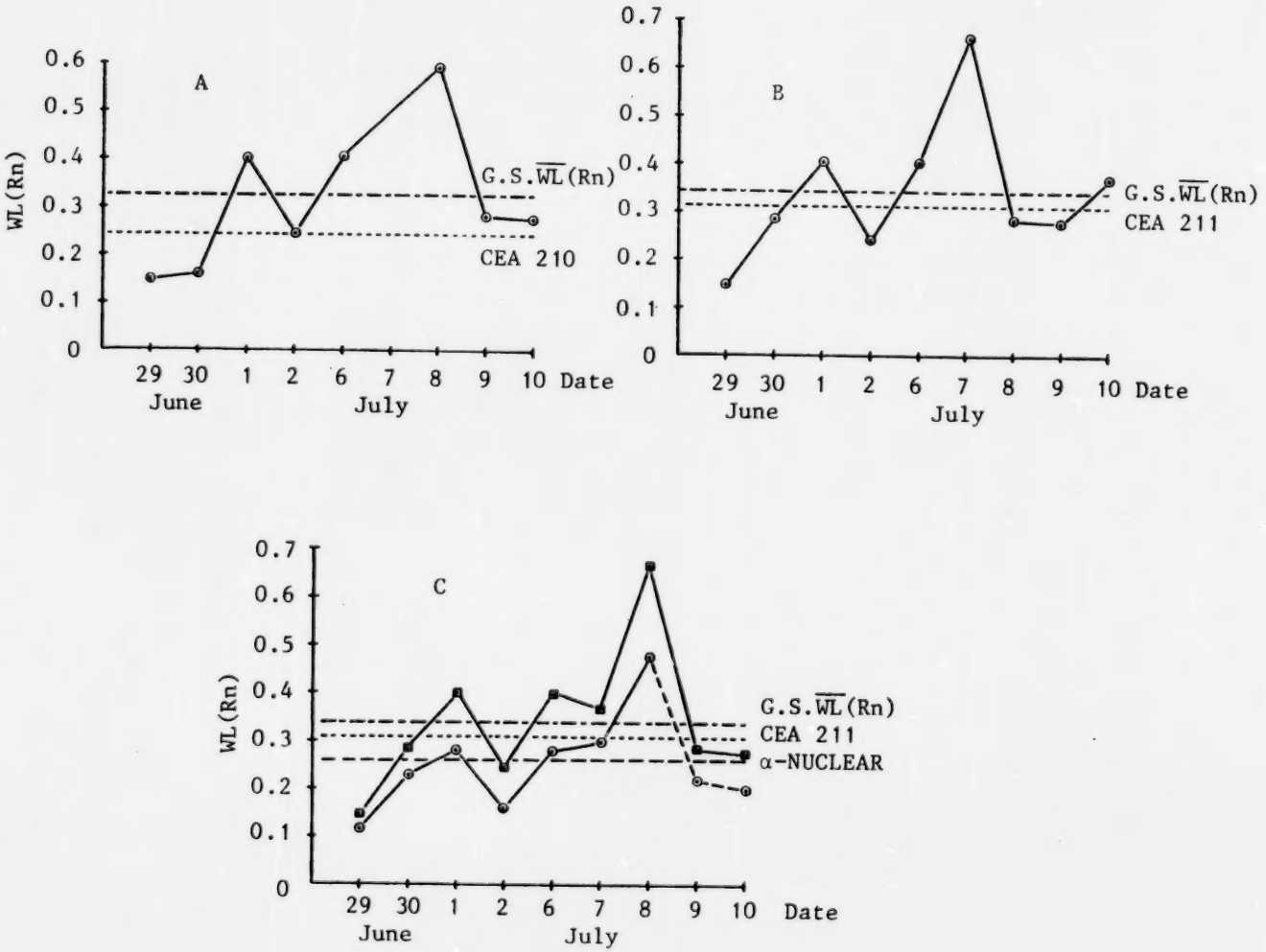



Fig. 68 - Daily average WL(Rn) versus date for grab-sampling (⊙ of graphs A and B and ⊡ of graph C). Also shown is the overall $\overline{WL}$(Rn) for track-etch dosimeters (---) CEA-210 and 211; grab-sampling (-·-, indicated by G.S.$\overline{WL}$(Rn); and α-NUCLEAR dosimeters (– – –), graph C); and daily WL(Rn) by α-NUCLEAR dosimeters (⊙ of graph C).

The α-activity and α-spectra of filters from the four dosimeter prototypes were measured as a function of sampling time by means of a ruggedized Si-barrier detector in conjunction with a multi-channel analyzer, as previously indicated. The α-spectra from the samples was compared with spectra obtained from standard radon daughter and thoron daughter sources by Pylon, type 190. (Note: in these sources activity is deposited on a filter by plate-out.) The data obtained in these studies provided information on items (2) and (3). Basically, and within experimental error, no appreciable difference was found in energy resolution and α-energy relative to the standard Pylon sources, although some spectral broadening and appreciable α-particle absorption was observed in the filter under loading conditions as compared with 'clean' and slightly loaded conditions. This subject will be dealt with elsewhere. Figure 69 shows spectra from a track-etch dosimeter filter. Curve A is a measurement carried out as soon as the filter could be measured in the laboratory, i.e., about 40 min after the end of underground sampling. In this spectrum the contribution from RaC' (middle peak) can still be clearly seen. Curve B shows the spectrum from the same filter sometime later. Notice that the RaC' contribution is considerably reduced because of its short half-life. (Note: the counting time for the two spectra is different. The spectra show α-counts versus channel number in the multi-channel analyzer.) The other two peaks of graphs A and B correspond to ThC and ThC'.

Alpha-spectroscopy was also used to determine and identify the long-lived radioactive component of mine dust. Filters from dosimeters were stored after the end of the tests for a few weeks for thoron daughters to decay away. (Radon daughter activity is reduced to a negligible amount about 4 hours after the sampling period.) Residual α-activity and α-spectra were measured. The details of this study will be published elsewhere.

Under continuous heavy dust and diesel load conditions a decrease in

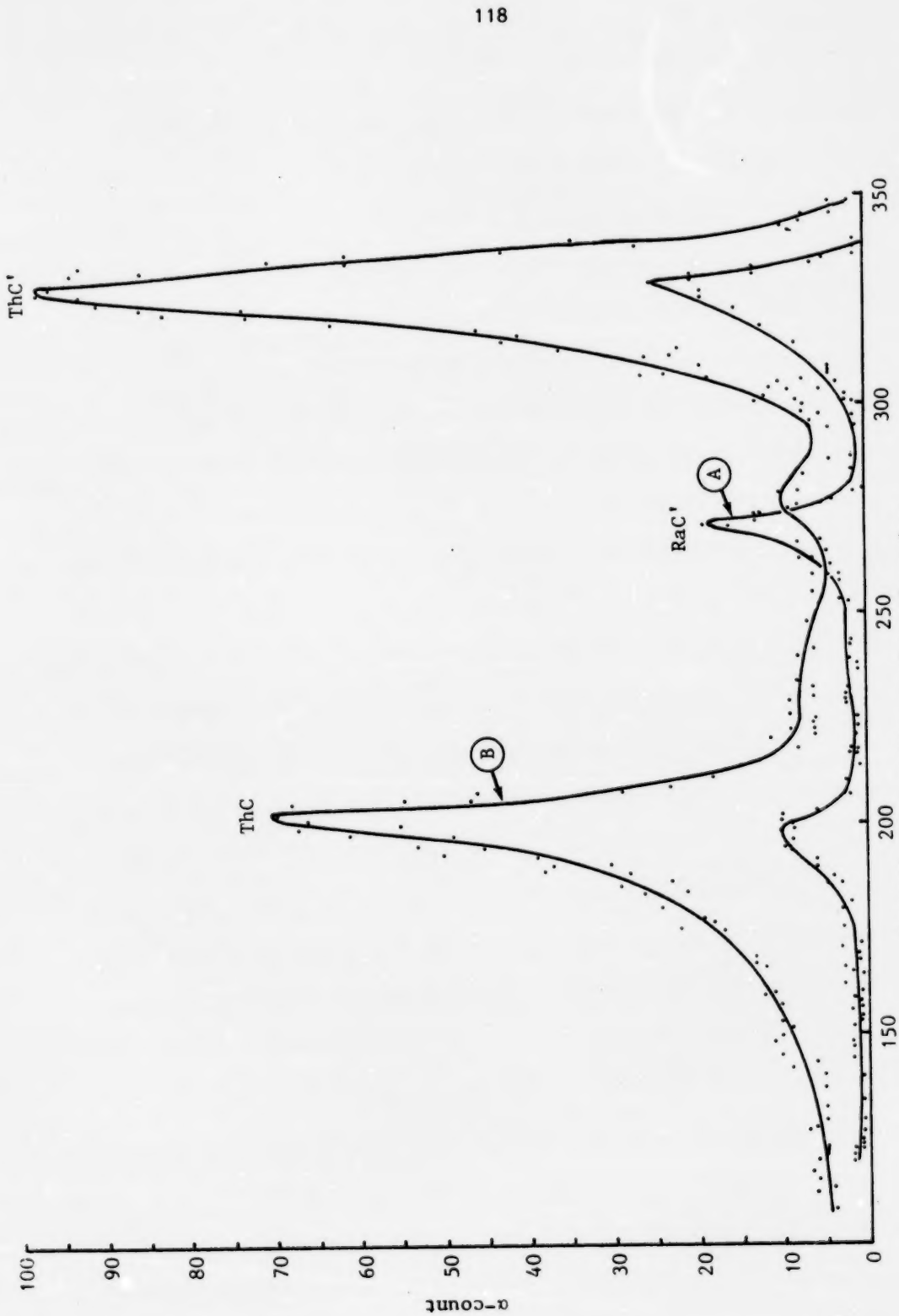



Fig. 69 - Alpha-spectra from an underground air sample measured at two different times after the end of sampling: graph A was measured 40 min after the end of sampling. Graph B shows the spectrum some time later. In the first case the contribution from RaC' can still be seen. The other peaks are ThC and ThC'. The counting time for B was considerably longer than for A.

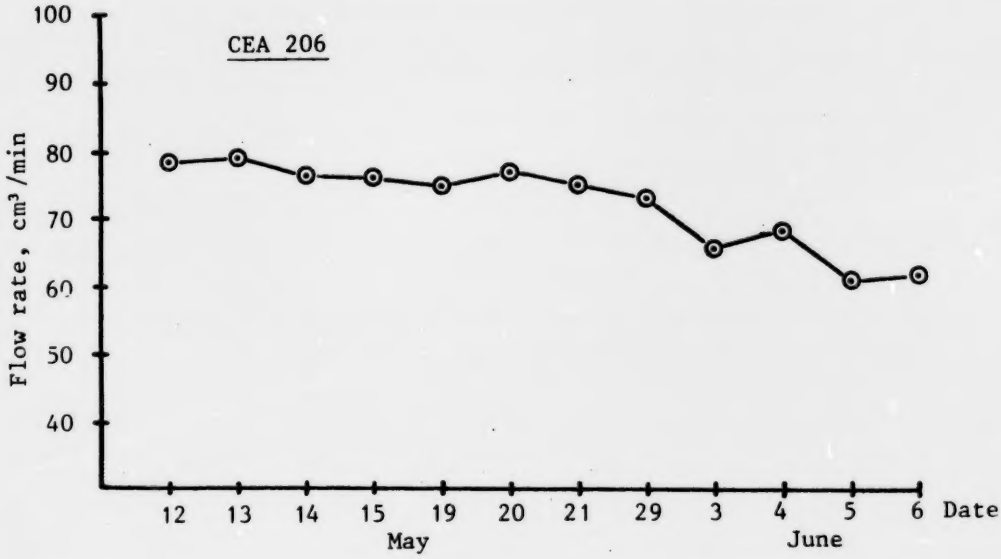
the track-etch and H & H dosimeter flow-rates was observed in the long-term underground tests, as shown in Fig. 70. This effect is attributed to loading of the filter by airborne particulates. This effect is not applicable to the α-NUCLEAR dosimeter and TLD/CAMPED sampler as in both cases the filter is changed daily.

## SUMMARY OF DOSIMETER PERFORMANCE, PRACTICAL DIFFICULTIES ENCOUNTERED, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

Although, in general, the tests proceeded smoothly, some difficulties arose at times that made analysis of the experimental data rather difficult. Some of the difficulties encountered are described below:

1) On occasions, some dosimeters were left in the lockers on surface, or were left underground after the end of the shift, or were removed from the belt and placed in a scooptram or muck pile. On at least three occasions there were signs of tampering resulting either in severe damage to the dosimeter, rendering it inoperative for some time, and/or total loss of the data for the test. Some filters were found pierced, the reason being unknown. This problem was identified because of the anomalously high dosimeter flow-rate measured when the dosimeters were brought to the surface. One dosimeter of each prototype was damaged in the course of the tests.

2. Several staff members of the ventilation departments at both mine companies participated (rotated duties) in conducting flow-rate measurements, programing the α-NUCLEAR dosimeter and changing the α-NUCLEAR filter. Six people rotated duties at Rio Algom, whereas three people were involved at Denison Mines. Hence, personal bias and human error due to the number of people involved in the tests were factors to consider in the analysis of the data obtained.



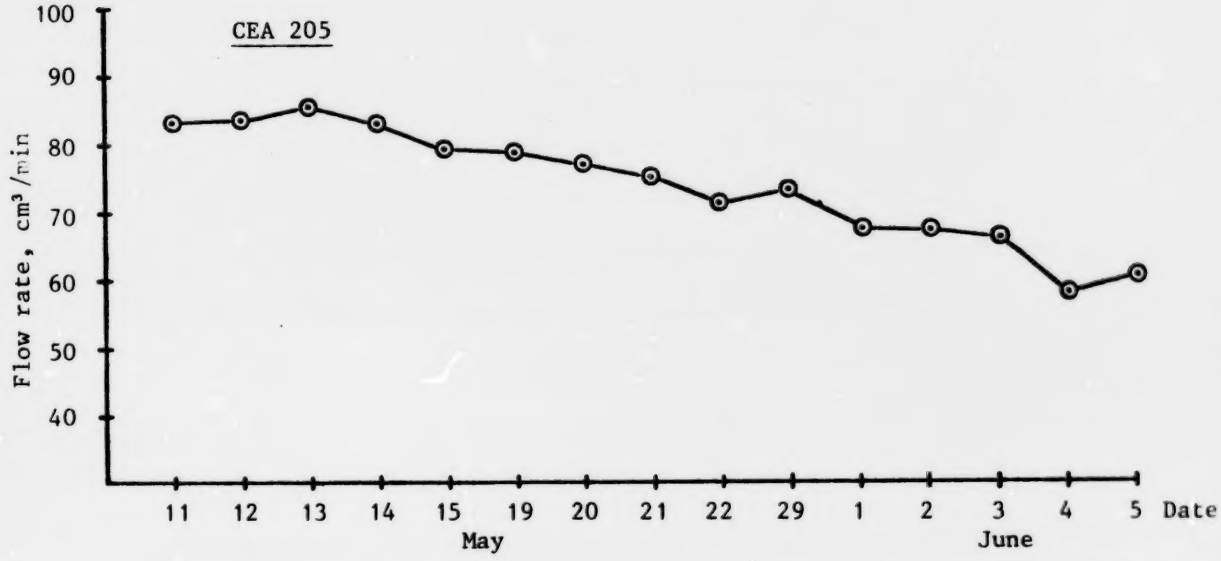




Fig. 70 - Dosimeter flow rate versus date for track-etch dosimeters CEA 206 and 205 in a diesel atmosphere.

3. Dosimeter malfunctions of mechanical type (e.g., sampling pump), such as those observed for 2 track-etch dosimeters and 3 H & H dosimeters or electronic type, such as that observed for the α-NUCLEAR dosimeter. Table 14 lists some of the most common malfunctions observed in the dosimeters tested. Some potential sources of error or malfunction are given in Table 15.
4. Wide range of underground environmental conditions as indicated in Table 16 and Fig. 1 and 38.
5. Variable miners time schedule, i.e., length of time spent in different areas including the cage, travelways, lounge room, refuge stations, garage, travel from surface to underground and vice versa, and working site(s).

The flow-rate of the TLD/CAMPED dosimeters remained quite constant over the working shift (2.1 L/min) and was adjusted daily to this value.

Flow-rate variations of about 30% were consistently measured for the track-etch dosimeters. α-NUCLEAR pumps gave better flow rate constancy, whereas large flow-rate variations (>30%) were observed for the H & H dosimeters.

In terms of pump durability the track-etch and TLD/CAMPED dosimeters performed best, followed by α-NUCLEAR dosimeters. H & H dosimeters did not perform as well as the other dosimeters. (It must be emphasized, as previously indicated, that the dosimeters used had been in operation for an indefinite period of time before our tests. It is, therefore, possible that newer pumps would have performed better.)

Good agreement was found for WL(Rn) as determined by α-NUCLEAR and track-etch dosimeters. Higher values for WL(Tn) were obtained with α-NUCLEAR dosimeters than with track-etch dosimeters. The WL(Tn) determined with α-NUCLEAR dosimeters was in closer agreement with grab-sampling data than that obtained with track-etch dosimeters. The behaviour and reproducibility of TLD

Table 14 - Most common malfunction or problems of dosimeter prototypes tested.

| Dosimeter | Observed by Miner | Cause A | Observed by Operator | Cause B | Dosimeter Pump Malfunction |
|---|---|---|---|---|---|
| α-NUCLEAR | Caplamp light dimming | i) Genuine problem<br>ii) Low line voltage<br>iii) Battery level low<br>iv) Battery cycling not adequate<br>v) Old battery | Occasional read-out problems | a) (i-v) of A<br>b) Genuine problem<br>c) Zeroing<br>d) Plug/unplug<br>e) Dirty contacts (reader/dos.)<br>f) Improper programing | 1 of 4 |
| H & H | None | N/A | Light contamination & filter loading | - | 3 of 6 |
| Track-etch | Handle cuts belt | Old handle did not fit, 'new' handle had sharp edges. | Severe contamination & filter loading | Faulty mechanical design | 2 of 16 |

Table 15 - Dosimeter potential sources of error or malfunction

| Dosimeter | Contamination | Filter Loading | Absorber Loading | Electronic Malfunction | Mechanical Design | Pump |
|---|---|---|---|---|---|---|
| α-NUCLEAR | No | No | N/A | Yes++ | No* | Yes |
| H & H | Yes | Yes | N/A | N/A | Yes+ | Yes |
| TLD/CAMPED | No | No | N/A | N/A | No | No |
| Track-etch | Yes | Yes | Yes | N/A | Yes | No |

+ Sampling head, clamp and unshielded TLD rubber holder

++ Electronic circuitry, diffused-junction detector or caused by low voltage on battery chargers.

* Ruggedness should be improved.

NOTE: sources of error common to all dosimeters are not included.

Table 16 - Range of values for some important environmental variables

| Variable | Range | Remarks |
|---|---|---|
| Temperature | 13-20°C | |
| Relative humidity | 75-95% | |
| Barometric pressure | 101-104 kPa | |
| Air flow | 2-80 $m^3$/sec | |
| [RaB]/[RaA] | 0.3-0.7 | Max $\simeq$ 0.5 |
| [RaC]/[RaA] | 0.15-0.5 | Max $\simeq$ 0.35 |
| Age of air | 30-40 min | |
| WL(Rn) | 0.08-0.3 | Occasionally slightly higher values+ |
| WL(Tn) | 0.06-0.35 | |
| WL(Tn)/WL(Rn) | 0.5-1.6 | |

+ Values for WL(Rn) higher than 0.3 were occasionally found in the leaching section of one of the mines. However, in this area, the leaching crew and environmental technician wore airstream type respirators for protection.

dosimeters (e.g., H & H and TLD/CAMPED) under our conditions were not as good as that of track-etch or α-NUCLEAR dosimeters. WL(Rn) and WL(Tn) for the α-NUCLEAR dosimeters were determined according to an analytical procedure described by Bigu elsewhere (19). Because of the complexity of the dosimetry problem, this analytical procedure makes certain simplifying assumptions which, although not strictly true, are nevertheless reasonable for practical purposes. The two main assumptions made are discussed below:

A. Constant dosimeter sampling flow-rate. The sampling flow-rate used in the calculations is that corresponding to values measured on surface at the end of the shift. However, appreciable flow-rate variation during the sampling period has been observed, e.g., up and above 20%, under field and laboratory conditions. As no direct access to flow-rate monitoring during the underground tests was possible this time, no accurate data on flow-rate are available, apart from those taken at the end of the shift;

B. Constant radon and thoron progeny concentration, and hence, WL(Rn), WL(Tn) and WL(Tn)/WL(Rn). However, appreciable radiation level fluctuations may occur at the working site because of local ventilation changes and/or mining operations. Radiation levels also vary from working site to travelways, lounge rooms, underground garages, 'cages' and the like, where miners spend variable amounts of time depending upon needs and circumstances. The derivation of analytical expressions for the case of non-constant radiation levels, even for simple cases, is a subject of great complexity and beyond the scope of this report.

The most reliable underground tests under reasonably controlled or well monitored conditions seem to indicate that all dosimeters underestimate WL(Rn) and WL(Tn) as compared with measurements determined by grab-sampling methods. The reason for this is partly attributed to the following. Data

have been analyzed assuming an 8-hour shift under constant sampling flow-rate and radiation level conditions, see items A and B. This 8-hour period includes travel time from and to surface, and hence under lower WL-conditions than that at the working site. It can be conservatively estimated that on the average, about 20% of the worker's shift-time might be spent in areas other than the working site, e.g., travelways, drifts, refuge stations, lounge room and the 'cage'. When full-shift dosimetry data are compared with grab-sampling data taken mainly at the working site the former are expected to be lower than the latter. This is precisely what has been observed, in general.

Other factors affect the accuracy of dosimetry data and their comparison with grab-sampling data. One such factor is the dosimeter sampling time as compared with the time taken for radon and thoron decay products to reach a steady-state condition in the sampling filter. This is of the order of 3 h and 12 h for radon daughters and thoron daughters, respectively (19).

Additional contributing factors include plate-out and filter 'self-absorption' because of filter loading, as indicated above. Plate-out of radioactive decay products in the dosimeter sampling head and other mechanical structures is highly dependent on geometry, sampling flow-rate and aerosol concentration. Plate-out in the α-NUCLEAR dosimeters was negligible. No plate-out measurements were carried out for the track-etch and H & H dosimeters although it is suspected to be appreciable on account of their geometries. Plate-out in the TLD/CAMPED dosimeter is expected to be high because of the unfavourable geometry for the collection of radioactive aerosols. This dosimeter was optimized for respirable dust collection.

Reproducibility of results was best for α-NUCLEAR and track-etch dosimeters followed by H & H and TLD/CAMPED dosimeters, in the above order.

Loading of the sampling filters by dust, diesel particulates and

moisture were found to affect the radiation response, especially for those dosimeters in which filters are changed less frequently, e.g., track-etch and H & H dosimeters. Filter loading effects observed for the track-etch consisted of a decrease in the pump flow-rate with increasing exposure time and a broadening of the α-spectrum under heavy loading conditions corresponding to the radon and thoron progenies. (These effects are not usually applicable to the α-NUCLEAR dosimeter where filters are changed daily.) Because of a lack of flow-rate reproducibility, these effects could not be adequately investigated in the H & H dosimeters.

Dosimeter prototypes which are designed to be read less frequently than daily (e.g., track-etch and H & H dosimeters, usually read monthly) cannot respond to sudden changes in WL such as those indicated in R.A.T.1 (Fig. 5). Hence, important WL 'spikes' are missed by the dosimeter and buried in a gross WL average.

Severe contamination of the detectors (e.g., cellulose nitrate) was observed in some of the track-etch dosimeters, thereby making track counting rather difficult (see Fig. 71). Occasional contamination problems were also observed in some H & H dosimeters. This contamination seemed to consist of long-lived radioactive dust as well as other airborne radioactive particulates. No appreciable contamination was observed for the TLD/CAMPED or α-NUCLEAR dosimeters.

In view of the experience gathered with the dosimeter prototypes tested here, the following recommendations are made:

1) The pumps on all dosimeters should be replaced by improved durability pumps with self-regulating flow control capabilities;
2) The pump and electronic circuitry in the α-NUCLEAR dosimeter should be such as to minimize power consumption;

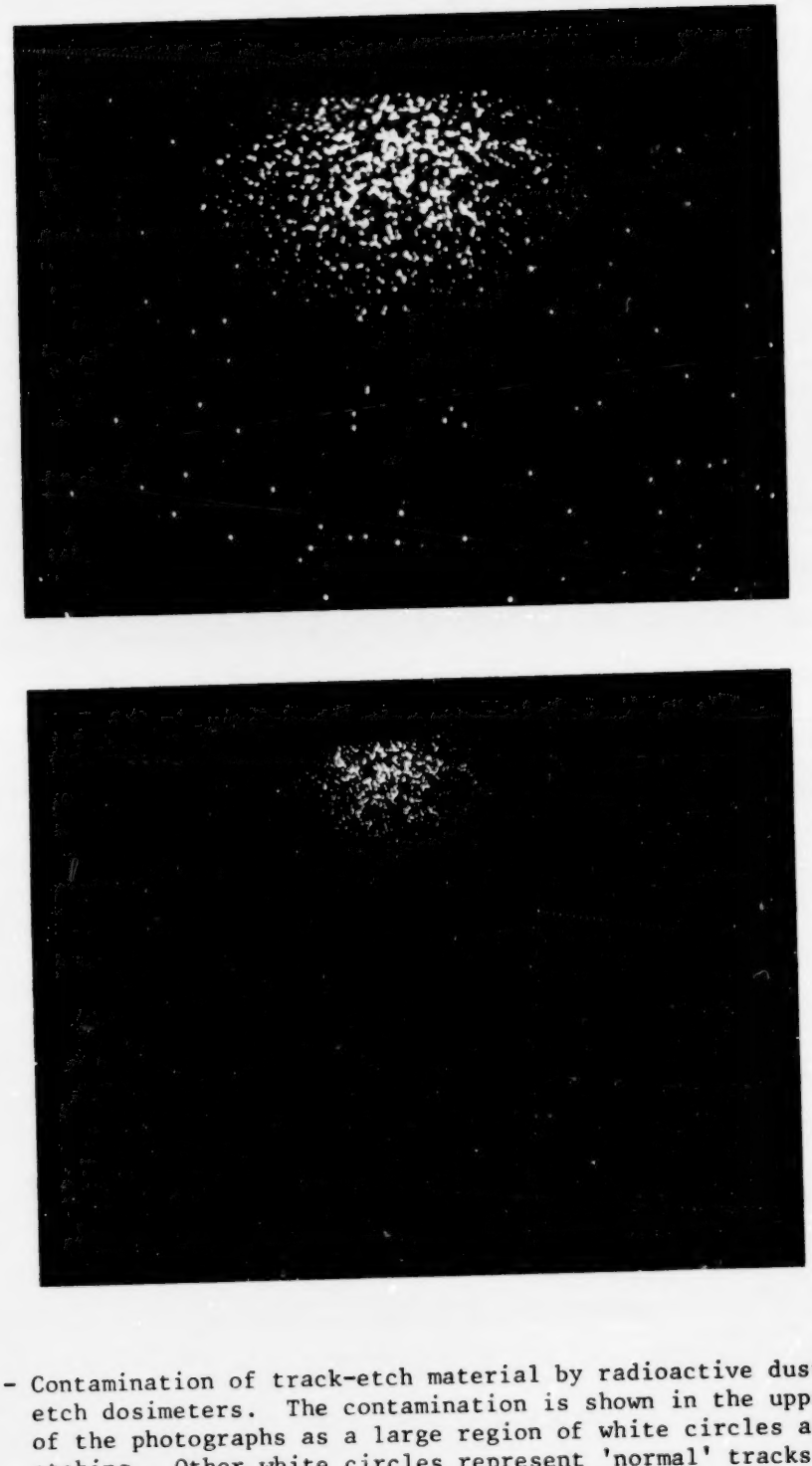


Fig. 71 - Contamination of track-etch material by radioactive dust in track-etch dosimeters. The contamination is shown in the upper portion of the photographs as a large region of white circles after chemical etching. Other white circles represent 'normal' tracks.

3) The sampling head of the track-etch dosimeter should be redesigned to eliminate radioactive contamination;

4) The sampling head of the α-NUCLEAR, track-etch and H & H dosimeters, although convenient when carefully handled, should be modified to make them less susceptible to mishandling, tampering and shock.

5) The TLD chip holder facing the filter of the H & H dosimeter should be changed or modified as occasionally the TLD chip falls off under shock and vibration.

Alpha-NUCLEAR and C.E.A. (France) have developed improved dosimeter prototypes that take into consideration the suggestions indicated in items 1 to 4.

From the observations, results and discussions presented here on the performance of the several dosimeter prototypes tested, it is evident that no single dosimeter fully meets the broad spectrum of ideal, practical requirements for routine personal monitoring, such as being inexpensive to build, simple to operate, easy to maintain and retrieve information from, has long-term reliability, and is, in addition, responsive to the thoron progeny present in relatively high amounts in some Canadian uranium mines. Some of the characteristics of the above dosimeters are given below:

TLD DOSIMETERS (H & H AND TLD/CAMPED SAMPLER)

a) TLD chips are cheap and re-usable but respond to different types of radiation (e.g., α, β, γ, UV, light) with different sensitivity. Thus more than one chip and shielding is necessary to determine α-dose. Reading of TLD chips is usually done after exposure to radiation for several days or weeks at a time;

b) TLD chips require careful handling as they are very sensitive to light, heat and some environmental factors. Some materials exhibit a phenomenon

called 'fading';

c) Once the information stored in the TLD chip is 'read', the information is lost;

d) Discrimination of thoron decay products is difficult.

TRACK-ETCH DOSIMETER (CEA DOSIMETER)

a) Insensitive to $\gamma$-radiation, hence no unwanted background;

b) Detector (i.e., cellulose nitrate) is cheap;

c) New dosimeter design enables discrimination of thoron progeny;

d) Detector requires chemical etching, a process which is time consuming and cumbersome. For large numbers of samples a highly automated 'reading' system is needed which makes initial investment rather high. Reading of the detector is usually done after exposure to radiation for several days or weeks at a time.

SOLID-STATE/ELECTRONIC DETECTORS ($\alpha$-NUCLEAR AND U.S.B.M. DOSIMETERS)

a) Detector (Silicon diffused junction or surface barrier detector) and associated electronic circuitry is relatively expensive and delicate;

b) Information (WLH or $\alpha$-counts) is directly read daily by means of an electronic reader in a matter of a few seconds;

c) Information can be retrieved at any chosen moment without loss of the information;

d) Discrimination of thoron decay products is possible by taking more than one reading on the same sample after the radon decay products have decayed away.

The $\alpha$-NUCLEAR solid-state dosimeter and the U.S.M.B. electronic dosimeter (a prototype designed by the U.S.B.M.) have been previously tested at an Elliot Lake uranium mine by CANMET (2).

There are advantages and disadvantages of the TLD, track-etch and electronic dosimeters over one another. One advantage of TLD and track-etch dosimeters over electronic dosimeters is that reading of the former is usually done every few weeks (e.g., monthly), thereby minimizing the amount of work required as compared with daily read-out for electronic dosimeters. However, TLD and track-etch readings are slow, tedious and time consuming, thereby off-setting some of the methodological simplicity indicated above. A distinct advantage of electronic dosimeters over the other prototypes is that daily dose exposure and hence exposure profiles, can easily be determined. It is also easy to detect anomalies in the performance of the dosimeter, whereas for the TLD and track-etch dosimeters a few weeks may elapse before certain malfunctions can be identified. Electronic dosimeters can also be used to identify ventilation characteristics and spot potential 'trouble' areas. Electronic dosimeters, are however, much more complex and delicate, and therefore, more susceptible to malfunction.

It is difficult to decide on the use of one type of dosimeter over the other. The choice must be based on a number of factors, including radiation response, life-time, ruggedness, initial investment and routine maintenance, and ease of operation, data processing and information retrieval.

Work should continue on personal dosimeters with improved design and capabilities based on the outcome of tests similar to the ones presented here.

Special emphasis should be placed in studying the response and performance of dosimeters under actual personnel working conditions in underground environments where environmental conditions are particularly harsh, rather than in laboratory calibration facilities. Furthermore, it is suggested that the radiation response of the dosimeters be compared with data obtained with continuous area monitoring systems rather than with grab-sampling methods

(involving a great deal of manual manipulation) which are, therefore, quite limited because of manpower restrictions and practical difficulties. In addition, more effort should be placed on the development of passive personal dosimeters to provide an alternative to the problem arising with the use of a mechanical pump, e.g., pump failure or malfunction and flow-rate variability, in active dosimeters.

The Elliot Lake Laboratory will be undertaking an underground technical evaluation, in early 1982, of improved versions of some dosimeter prototypes discussed here, and of new ones, in conjunction with continuous area monitoring techniques.

## ACKNOWLEDGEMENTS

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The authors are grateful to the AECB for their interest in this work and for the loan of the track-etch dosimeters and H & H dosimeters used in this technical evaluation.

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